



Cracking behaviour in 3D concrete printed fibre-reinforced cementitious composites: A review

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ABSTRACT

The integration of 3D concrete printing (3DCP) technology in cementitious composites offers significant opportunities, particularly in enhancing material efficiency and enabling greater design flexibility. However, the layer-by-layer deposition process introduces new challenges, especially regarding crack formation due to factors such as weak interfacial bonding and anisotropic mechanical behaviour. Fiber reinforcement has emerged as an effective strategy to mitigate crack development and enhance overall mechanical performance. This review examines the primary causes of crack initiation, key influencing factors, and mitigation strategies in 3DCP fibre-reinforced cementitious composites. Initially, it analyses crack formation in conventional cement-based materials, focusing on mechanisms of crack initiation, propagation triggers, and challenges associated with crack control. Traditional approaches such as steel reinforcement and chemical admixtures are also discussed. The review then explores recent advances in 3DCP techniques, including material selection, the role of anisotropy, and interlayer adhesion. Experimental findings suggest that maintaining a mini-slump flow diameter between 127 mm and 203 mm ensures suitable printability, while additives such as silica fume improve resistance to cracking. The nature of fracture propagation throughout the 3DCP process is specifically examined, emphasising how printing factors affect the evolution of cracks. An overview of the computational, experimental, and microstructural approaches for assessing crack behaviour is also included in the paper. Finally, the role of fibre characteristics, such as orientation, bridging mechanisms, and aspect ratio, is evaluated in relation to their effect on crack control in 3DCP composites. By synthesizing these findings, the study demonstrates pathways to enhance the durability and mechanical integrity of 3DCP fibre-reinforced cementitious composites, ultimately contributing to improved crack resistance and broader adoption of 3DCP in construction materials.

1. Introduction

Cementitious composites have played a critical role in the construction industry since it was proposed in the 1990s by Li and Leung [1] to investigate fibres and matrix effects on mechanical properties. The benefits of cementitious composites rely on their durability, versatility, and efficiency, catering to practical applications in modern construction. Despite the challenges that are involved in the usage of cementitious composites, they have taken their first steps in civil structures in terms of functional materials providing higher

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integrity and architectural aesthetics [2]. According to a variety of attempts, cementitious composites made using specialised materials meet mechanical needs, are environmentally sustainable, and last longer [3,4].

Cracking in the construction materials is an influential factor that not only depends on mechanical interactions in the matrix but also poses the strength capacity and safety risk of cement-based materials [5]. According to this perspective, recent developments in cementitious materials have concentrated on fracture behaviours in an attempt to create strategies for enhancing their resilience [6]. As regards, the plastic shrinkage cracking in cementitious composites was mitigated by utilizing polymer-based fibres, serving an improved performance on wide surfaces [7].

On the other hand, there have been some requirements of the present construction process, such as enabling complicated geometries and polished material characteristics, which have been fulfilled with the hybrid of fibre reinforcement and 3D concrete printing (3DCP) technology [8]. This emerging procedure is also deemed as a potential approach for both advanced design and fabrication with customized ability and cost-effective methods. Within this framework, various lightweight constructions were created using 3DCP and fibres to reduce product resistance to quasi-static, dynamic, and thermomechanical loadings [9,10].

1.1. Significance of cracking in cementitious composites

The service life and structural stability of cementitious composites can significantly be impacted by cracking in different aspects including the load-bearing capability and a higher fragility against unpredicted phenomena [11]. Such events, creep, fatigue, and stress corrosion cracking usually lead cement-based structures to premature failure and a higher maintenance expense. In this way, if the structures are exposed to crack-induced failures, considerable economic losses and environmental impacts are forced on the projects because of lower lifespan and the growth of resource consumption in the fixing process [12,13].

Cracks are considered a significant disadvantage in cementitious composite due to their limited deformation ability leading to brittle cracking. The main criteria used to assess the durability and integrity of cementitious surfaces are common causes of fractures, including loading conditions, environmental factors, and shrinkage during the curing process [14]. Table 1 expresses some studies that used a bunch of causes for cracking in concrete and cementitious composites. Due to the involvement of a wide range of sources in cracking, it remains a complex challenge to find feasible mitigation strategies [15].

Traditional approaches, such as additive manufacturing and steel reinforcement, have shown some feasible materials although often fall short in managing the intrinsic multifaceted feature of cracking [16]. On this point, efforts in the field presented the corrosion of steel reinforcement [17] and bond characteristics between steel fibres and cementitious composites [18] as effective factors for creating cracks. Since the complexity of the crack expansion, there is a growing need for introducing innovative cementitious composites with higher flexibility to crack causes, especially advanced materials that are fibre reinforced using the 3DCP [19].

1.2. Role of 3D concrete printing in cementitious materials

The 3DCP technology has evolved from limited laboratory tools to a viable method in the construction industry through customized products and efficient performance. The common sources of fractures, such as shrinkage during the curing process, environmental influences, and loading conditions, are primarily evaluated for durability and integrity in cementitious surfaces [20,21]. The design flexibility and optimizing the materials in terms of mechanical response, weight, and quality are other captivating features of the 3DCP, which lead to create desired geometry and special materials like lightweight cementitious composites [8,22].

Among the available 3DCP technologies, the extrusion-based technique is the most popular in additive manufacturing, in which a cementitious mixture is fabricated through a nozzle to form continuous filaments [23]. Its simplicity and compatibility with fibre addition to input materials define it as a promising method for the 3DCP development in structural applications. Despite the fact that extruding the cementitious materials could make dominant strength properties, its layer-by-layer feature is prone to anisotropy, and the fragile interlayer contributed to crack propagation, which are explained in the present review [24,25].

Other techniques, such as binder jetting or powder-based printing, are less prevalent but deliver some unparalleled characteristics of the 3DCP technology. Binder jetting is an advanced 3DCP technology with diversity in building complex architectural components and providing precisely designed materials. These characteristics and mechanical achievements have ranked its feasibility similar to the extrusion-based technique [26]. The fibre distribution and printing factors are influential parameters on the mechanical responses

Table 1
The causes for crack initiation in concrete and cementitious composites.

Reference	Cracking cause
Dhir & Yap [28]	Early-age drying shrinkage
Sanjuan & Moragues [29]	Plastic shrinkage due to polynomial function
Hoersch & Wittmann [30]	Cyclic freeze-thaw damage
Buyukozturk et al. [31]	Fiber debonding under cyclic loads
Mazloom [32]	Long-term creep and shrinkage
Islam et al. [33]	Salt crystallization in coastal environments
Mpalaskas et al. [34]	Fiber pull-out under tension
Li et al. [35]	Thermal stress
Xue et al. [36]	Material incompatibility
Yanbo Wang et al. [37]	Environmental effects (freeze-thaw cycles)

of the powder-based 3DCP method, which form crack paths [27].

The benefits of the 3DCP over traditional casting techniques have been proved in some tricky angles where the modern fabricating machine allows for fast prototyping, reducing waste, and enabling the connection of automated systems in the process [38]. The advantages of the 3DCP contributed to cracking are mainly described in its unique fabricating step when the outcome contains the absence of large air voids, compaction of layers, and effective fibre orientation. The superiority of this manufacturing technique is demonstrated by the strength, flexibility, crack patterns, and durability of cementitious composites [39,40].

Since the introduction of 3D concrete printing as a cutting-edge construction method in 1997 [41], it has witnessed a number of innovations. Fig. 1 shows two types of 3DCP development in a timeline including the creative approaches in the manufacturing and quality of cementitious materials in its lower side with black colour. The upper side expresses the development of evaluation in understanding and mitigating crack behaviour for 3DCP products.

The 3DCP is also a potential solution for compatibility issues in the building industry, as the technology reduces material waste and allows for the inclusion of recycled materials. In this context, waste tire rubber particles [42] and recycled sands [43] in the mix design of the 3DCP not only presented eco-sustainable printable materials but also obtained an alleviated performance against deformation and cracks. Enabling the application of state-of-the-art materials, for instance, fibres and additives, in the 3DCP, leading the material engineering field to crack-resistant products in a digitalized manner. Regarding the fibre's role, polyethylene (PE) fibre made by the 3DCP showed considerable growth in strain-hardening behaviour and prepared the multi-cracking reaction in the engineered cementitious composites (ECC) [44].

The ECC materials are practical examples of cementitious composites employed in urban and civil structures such as bridges and housing components [53]. Furthermore, in such infrastructures, ECC is a suitable material for delivering sustainability for the process with lower cost [54]. Implementing the ECC materials with the 3DCP technology improved their benefits in presenting strain-hardening features compared to the normal ECC and conventional cementitious composites [55]. Fig. 2 illustrates flexural loading results in comparing the fibre-reinforced normal concrete with ECC materials (left side) [56] and the cast with printed ECC (right side) [57].

Regarding the evident difference between the ECC and conventional concrete (Fig. 2, left side), the strain-hardening properties of ECC materials turned the brittle failure of the concrete into a ductile failure under flexural loading. This behaviour shifted the ratio of flexural strength to the tensile strength (maximum load bearing) from 1 to 3 to 5 in the concrete to ECC samples.

In Fig. 2, right side, the graphs include the mold cast and printed flexural trends, the bending performance of the printed ECC (Y and Z directions) indicated growth versus the cast ECC, especially in the strain-hardening stage with an increased deflection around 50 mm. Therefore, the 3DCP process influences not only the failure mode but also the crack propagation associated with the bending response of cementitious composites. In addition to the ECC materials, other types of advanced materials, such as engineered geopolymer composites (EGC) and ultra-high-performance concrete (UHPC), which achieved superior strength components [58] and resilience against extreme environments [59], benefited from the 3DCP [60].

1.3. Scope and objectives of the review

Evaluating the crack behaviours in 3D-printed cementitious materials is highly significant due to their contribution to the mechanical properties, structural reliability, and rehabilitation plans [61]. Furthermore, hotspots for possible innovative ways to utilise the cementitious materials produced by the 3DCP are identified through fracture interpretation. If we consider cracks as a likely pathway for deleterious agents such as carbon dioxide, which can threaten cement-based structures, polypropylene (PP) fibres were proven to mitigate the issue to some extent [62].

Despite the progress in evaluations of the fibre-reinforced 3DCP cementitious materials, there remains a gap in gathering the comprehensive efforts that were conducted for the interaction between the 3DCP factors and materials characteristics. This review, based on the crack investigation, tries to consolidate experimental plans and numerical simulations that create a deeper perception of

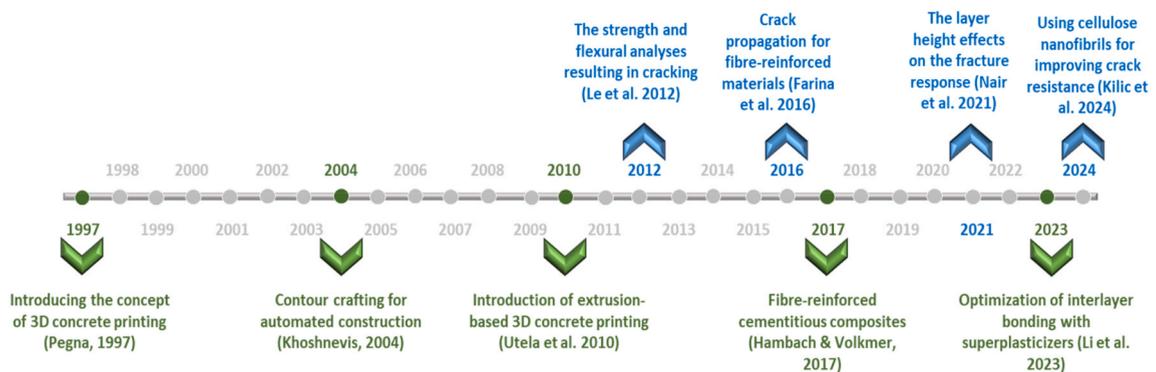


Fig. 1. The 3D concrete printing technology developments. Upper section: evaluation in mitigating crack expansion. Lower section: creative approaches in manufacturing [41,45–52].

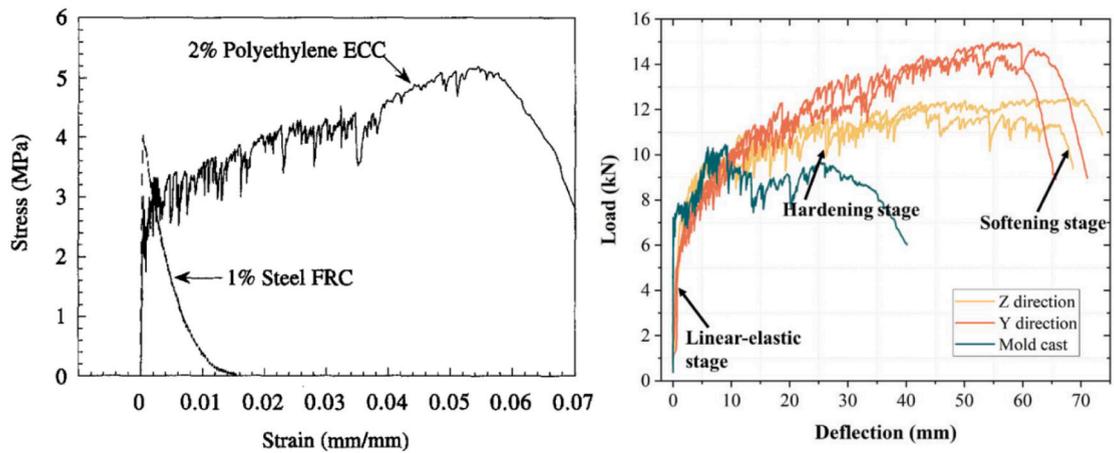


Fig. 2. The results of flexural bending load on the normal fibre-reinforced concrete (FRC) and engineered cementitious composites (ECC) (left side) [56]; The flexural loading outcomes of printed samples (Y and Z loading directions) and mold cast [57].

crack mechanisms in the 3DCP composites. These insights are completed by describing the printing parameters’ effects on the crack propagation which are a part of microstructural interpretation in cement-based materials.

In detail of the review paper, studies that focused on the crack behaviour of fibre-reinforced cementitious composites, especially in the 3DCP process, are presented in four levels. Analyses in material, process, structural, or microstructural, and performance stages are included in the review. Fig. 3 illustrates the framework of the given stages, where they cover the crack interpretation process in various aspects of the 3DCP from fibre-matrix interaction to mechanical response of fabricated materials. These evaluations are described in the following sections using theoretical conceptions and outcomes acquired from existing efforts.

In addition, this paper seeks to introduce possible areas for research and practical implementations in the industry by highlighting recent developments and diagnosing the gaps in studies. In this way, the review will focus on key themes including fibres roles in crack patterns, traditional cracking mechanisms, applications, and changes in 3DCP for cementitious composites.

2. Crack behaviour in traditional cementitious composites

The first step in determining fracture behaviour in concrete is to identify the causes of initiation. Cracks are often traced to places with poor interfacial characteristics between the matrix and aggregates [63]. It propagates under stress that is defined in fracture mechanics as a critical intensity factor and can direct the cementitious composites (concrete, mortar, and fibre-reinforced mortar) to failures [64].

There are some key factors affecting the crack spreading such as loading conditions, material constitution, and natural influences in

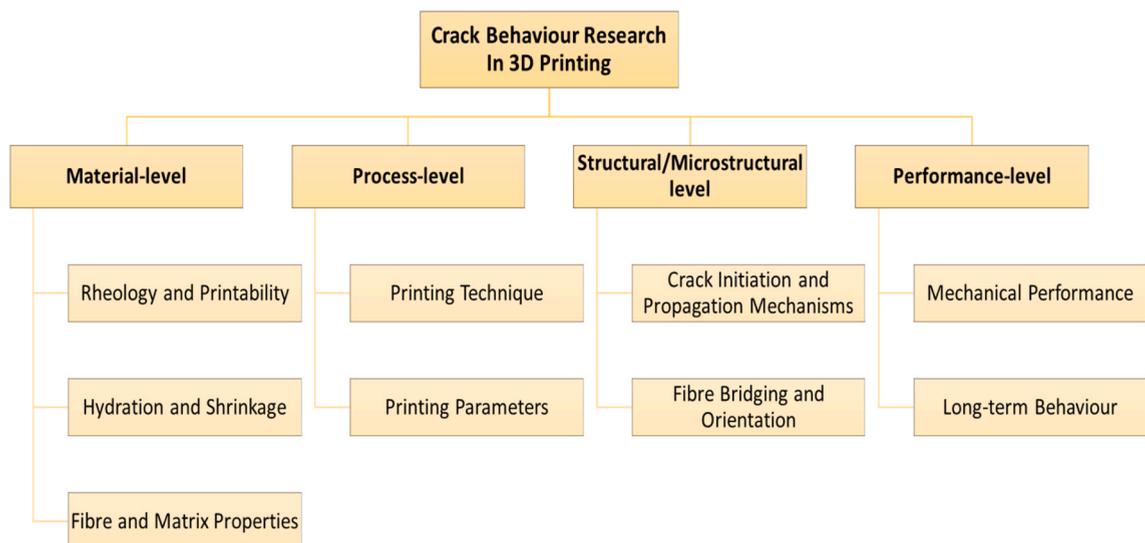


Fig. 3. The framework of the present review for the crack behaviour research evaluations.

cement-based materials [65]. The mentioned factors have also critical functions in the likelihood and intensity of cracks [66]. When it comes to traditional cementitious materials, the main strategies that are applied to deal with cracks such as additives and reinforcements have some constraints like reinforcing elements making new paths for cracks or additives causing higher costs [67].

2.1. Crack initiation and propagation mechanisms

Cracks are identified to be initiated from sub-microcracks that are in the range of 2.5 width against the microcracks with 0.1 mm of width [68]. Next, through originating the microcracks in the first step of cracking, they are visible at the microstructural level with the naked eye. The following describes how loading and pore structure, respectively, affect the microcracks' ability to spread, enlarge, and join with adjacent discontinuities [69].

Stress concentration is known for forming localized cracks, especially tensile fractures, which are triggered by flaws and interfaces. Furthermore, stress conducts the pathway for crack propagation on the surface or throughout the structure [70]. The crack formation and expanding conditions are also influenced by the hydration process and the alteration in material characteristics like heterogeneity features. Basically, concrete is classified among highly heterogeneous materials. Some studies [71,72] proved the heterogeneity in the microstructures level of cementitious composites is not only a challenging matter in modelling the failure and strength but also large voids and interphase between layers are its growing factor.

In addition to the stress and material properties, some circumstances with implementing mechanical pressure, thermal expansion, and environmental impact were presented for decreasing or accelerating the cracking [73]. Table 2 shows some studies that were deemed to investigate the loading, thermal, and environmental effects on the fracture mechanisms of fibre-reinforced cementitious composites. Given the constant advancements in cement-based products, the use of 3DCP technology, and the fact that cement is used in many different types of structures, it is always necessary to evaluate the fundamental causes of fractures in them. As described in Table 2, experiments found that cracking mechanisms and initiatives were applied in that way to control the crack initiations.

2.2. Factors affecting cracking (shrinkage, loading, etc.)

Shrinkage under the hydration process is one of the major factors for conducting cracks in traditional concrete and cementitious composites. The hydration effects have been mostly presented for promoting tensile stresses which initiate fractures if they pass tensile strength of materials [74]. The crack growth in cements is also influenced by repeated loading cycles that make fatigue tension leading to degrading the connection in matrix and aggregates. Since the ECC's fibre bridging stress, a governing factor for crack propagation, diminishes with increasing loading cycles, the effects of fatigue tensile loading are ascribed to the materials as well as the number of cycles and time [75,76].

Furthermore, in some circumstances, stress gradients are generated by subjecting to temperature fluctuations or sources for making thermal stresses. The given stresses are crack drivers resulting in thermal expansion to various extents based on the material properties [77]. Besides, crack development in cement is formed in the carbonation process as a result of chemical interactions when they compound with specific environmental surroundings. The number and volume of pores in cementitious materials are very important for carbonation [78].

The pores geometry is a critical point in the difference between traditional and 3D printed cementitious composites, which will be expanded in Section 4. All the mentioned influential factors on the crack expansion including hydration, loading, high temperature, and carbonation can be involved in real conditions for the cement-based materials, thus, a holistic approach for determining the crack behaviours is vital.

Table 2

Studies that investigated the loading, thermal, and environmental effects on the fracture mechanisms of fibre-reinforced cementitious composites.

Reference	Impact type			Mechanism	Effects on cracks
	Loading	Thermal	Environmental		
Wang et al. [81]	✓			Mechanical loading on recycled fibre-reinforced concrete.	Increasing post-cracking behaviour, harnessing crack widths.
Kasemchaisiri [82]			✓	Self-compacting concrete (SCC) exposed to sulfate.	Concrete in sodium sulfate atmosphere led to higher cracking rate.
Li M. & Li V [83]			✓	Engineered cementitious composites (ECC) exposed to chloride.	ECC exhibited tight crack width control, which delayed corrosion.
Szelag [84]		✓		Applied high temperatures to carbon reinforced cement paste.	Carbon nanotubes increased stability and self-healing of cracks.
Wang et al. [85]		✓		Glass fibre-reinforced 3D printed samples subjected to -10°C environment.	Low temperature increased material brittleness and boosted fast crack growth.
Du & Qian [86]	✓			Fibre-reinforced 3D samples printed in two directions and applied the loading.	Higher anisotropy and fracture strength in the paralleled-printed than cross-printed.

2.3. Limitations of conventional techniques in crack mitigation

The traditional reinforcement methods such as steel bars and welded wire mesh were effective combinations with cement ingredients to mitigate cracks, however, they were associated with crack propagation in the longer term. Where steel bars were susceptible to corrosion and made a significant challenge for the durability of cementitious materials [79,80]. Fig. 4 shows two cementitious surfaces for corrosion evaluation when steel bars (Section A) and welded wire mesh (Section B) were employed in the structure. As it is obvious, the points with the interaction of traditional reinforced material and cement were origination and pathways for cracks.

Enhancing the crack prevention features of cement-based products was followed by incorporating admixtures to their mix design along with trying reinforcing materials. Studies expressed both the benefits and drawbacks of admixtures. For the advantages, the prevention of early-age autogenous shrinkage cracking [87] and an increase in the healing capacity of cementitious composites [88] were considered. Conversely, the superabsorbent polymers (SAPs) and expansive admixtures (EXAs) were found to be extremely dependent on their ideal dose and to create voids when added to mixtures in order to increase their mechanical characteristics.

What is more, employing admixtures was linked to higher costs in structures especially in large-scale projects [89]. However, their features in improving the sustainability of developments are incentives for wide usage. Therefore, the reviewed traditional methods for mitigating the cracks in cementitious composites have not demonstrated a long-term strategy. It also indicates a need for combining innovative materials and construction practices to boost the performance in tackling cracks in cement-based products.

2.4. Discussion of section 2

Section 2 exhibits a structured framework of traditional cementitious composites in crack initiation and propagation conditions as a result of shrinkage, loading, thermal implementation, and environmental circumstances. Meanwhile, microstructural heterogeneity and interfacial weakness mechanisms are introduced as consistent origins for creating cracks. Such cracking emphasizes the importance of cracks not only in mechanical evaluations but also as a multi-scale issue contributing to material composition, curing, and surrounding elements. The section establishes the significant challenges of traditional cement-based materials, such as trade-off reinforcements and high-cost admixtures, which constrain long-term performance.

Although the challenges deterred previous developments, the review underscores opportunities that the experiences of conventional composites present in designing new 3DCP fibre-reinforced procedures. For innovative perspectives, the reviews of the section suggest combining traditional knowledge with modern strategies. These initiatives facilitate systems with hybrid reinforcement methods, cost-effective admixtures, and digital crack detection tools. The outcome can cover the limitations of conventional methods and be prepared for real-world loading conditions.

3. Advances in 3D concrete printing of cementitious composites

Based on the experiences, some advancements in the 3DCP have been applied that made it a promising technology. One of its key breakthroughs is manufacturing complex geometries while enabling structures with increased mechanical properties [90]. In this way, 3D-printed slabs with hollow sections and lightweight ECC materials met self-reinforcement and a higher flexural strength-to-mass ratio [91].

Despite considerable progress in the 3DCP field, there are still some challenging points associated with its scalability, product characteristics, and essential approval steps [92]. Crack behaviours in the 3DCP revolution are related to both material properties and legal acceptance due to the effects on the reliability of structures. 3DCP case studies from around the world have shown how well small and medium project sizes can be used. They were initially employed in the building of homes, artwork, and furniture for the streets [93].

3.1. 3D concrete printing techniques (extrusion, binder jetting, etc.)

The 3DCP technology has been presented in different methods through the years to optimize and satisfy various construction



Fig. 4. Two surfaces of cementitious materials. Section A: steel bars effect, Section B: welded wire mesh impacts [79,80].

demands. The extrusion-based 3DCP is the most common method that fabricates cementitious composites with continuous flow from a nozzle to form layers [23]. The extrusion technique provides a competent strength because of two technical benefits, packing materials in dense layers and powerful interlayer bonding [94].

The binder jetting as an innovative version of 3DCP techniques works with selectively depositing a liquid binder on a surface with cementitious materials in a powder shape. Its high-resolution print usually builds porous materials with low mechanical strength [95]. Fig. 5 illustrates the binder jetting 3DCP (Section A) [96] in two steps including recoating phase and binder spraying and the extrusion-based 3DCP (Section B). The extrusion method requires setting optimal speed and extrusion factors to reach the desired layers [97].

Making the decision for a suitable 3DCP technique contributes to the unique application of the methods and project requirements. Sometimes, the hybrid of the 3DCP and conventional construction is deemed for building large-scale structures [98], which can cover the lack of knowledge of the 3DCP settings on sites. Moreover, scaling the 3DCP products up for large-scale structures is another technical and economic difficulty, directing this technology to innovative solutions.

3.2. Materials for 3D printed cementitious composites

Studies into the optimal mix design for the 3DCP have resulted in the creation of materials with tailored rheological parameters to experience better printing outcomes [99]. Fig. 6 shows the range of flowability based on the mini-slump test's spread diameter for the mix designs when they were fed into the 3DCP in some studies. The purposes of the studies were mainly ECC and lightweight materials and their average range for ideal performance of 3D printer was calculated between 146 and 182 mm of spread diameter.

Some effective supplementary materials such as silica fume and fly ash not only improve the printability and workability of 3DCP mix designs but also boost vital mechanical properties. As a result, silica fume as a supplementary material effectively influenced the flow and penetration resistance of the given mix, as well as reducing the maximum number of layers and yield stress [100]. The drying shrinkage and the cracks of plastic shrinkage were introduced as contributed to the addition of silica fume, where adding 3–6 % of silica fume, respectively increased and reduced the drying shrinkage and flexural strength by 5 and 4 % [101]. The given factors are significant in crack propagation patterns in cementitious composites.

There is a considerable attempt to develop sustainable materials for the 3DCP, which their creative products spread from the reprocessed aggregates to bio-inspired binders [102]. To this extent, Fig. 7 shows the outcomes of compressive tests on specimens of a related study [103], where, Fig. 7-A and -B are respectively 3D printed samples from natural and recycled fine aggregates. They discovered that materials using recycled sands showed very identical load bearing and crack propagation patterns to natural sand materials.

In the research, the resemblance of their crack patterns is evident in Fig. 7. The displacements of the natural and recycled specimens, however, were 5.2 and 2.5 mm, respectively, suggesting that the recycled specimen was more brittle. Shifting the brittle

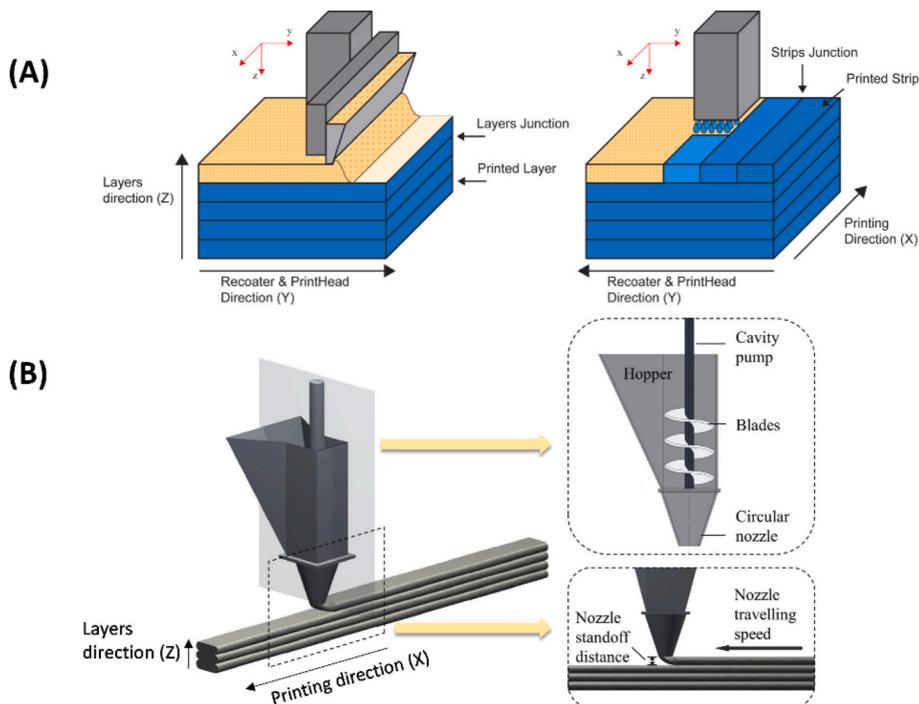


Fig. 5. The 3D concrete printing methods. Section A: binder jetting, Section B: extrusion-based method [96,97].

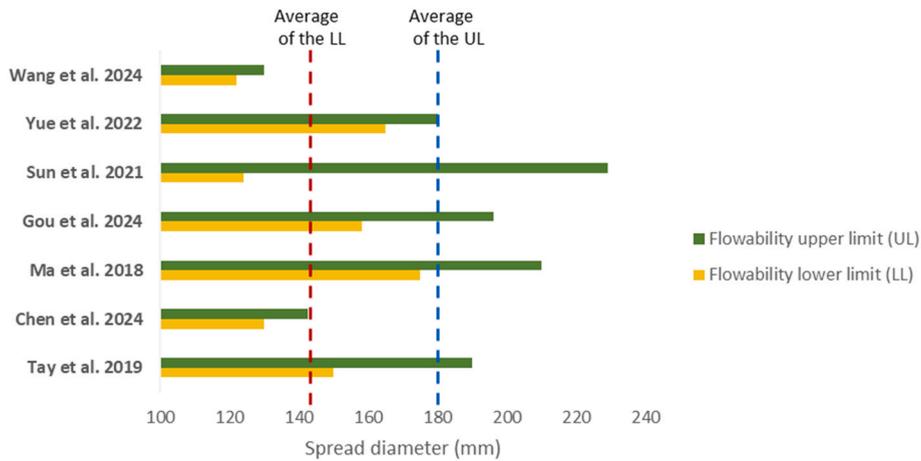


Fig. 6. The flowability range of the mini-slump test using the spread diameter applied in the previous studies. References: [24,105–110].

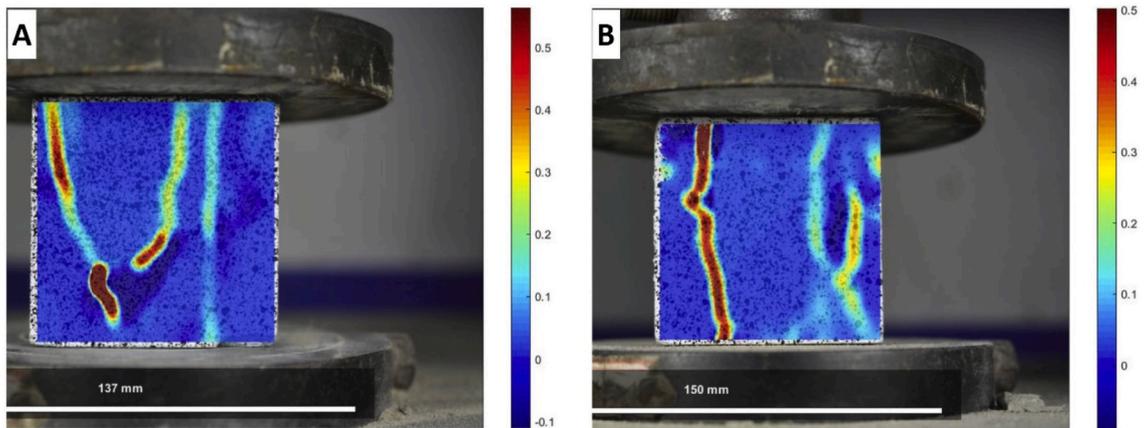


Fig. 7. The results of crack interpretation on the compressive test. Section A: natural fine aggregates, Section B: recycled fine aggregates [103].

characteristics of recycled materials to ductile is possible using fibres [104] that are described in Section 5. Reviewed studies marked the importance of finding cementitious materials with a balance of stability, ductility, and sustainability that require employing optimization in the process of manufacturing.

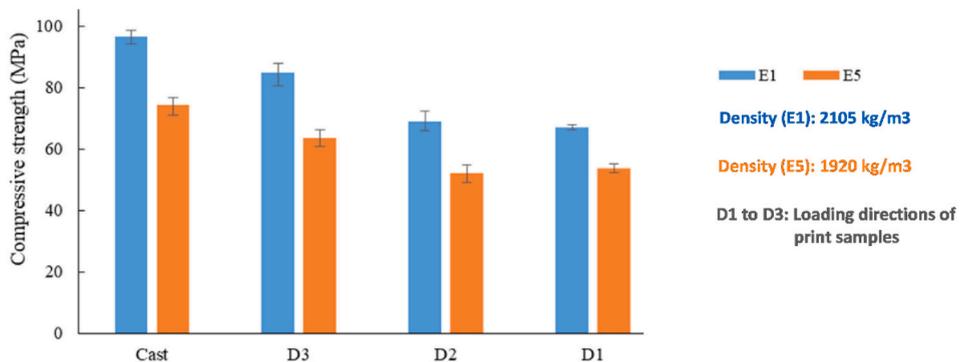


Fig. 8. The results of compressive strength tests on the cast and printed samples (three loading directions) with two densities, E1 and E5 [108].

3.3. Advantages and challenges of 3D concrete printing in construction

The 3DCP presents unparalleled flexibility in the modelling and implementation of complicated geometries and likewise benefits the project with optimal usage of materials [111]. Despite this advantage that comes from the 3DCP’s fabricating procedure, it encounters some difficulties in obtaining uniform material properties through layers, which influences the crack expansion in the structure [112]. According to the experiments [113], the crack propagation of the 3DCP indicated a stable expansion by reducing unstable routes across the interlayers and increasing crack initiation along the interlayers.

In addition, the natural anisotropy of the 3DCP materials that affect the crack behaviour is a critical aspect of the technology. However, improving the bond adhesion between connected layers in the printed structure was introduced as a solution for alleviating the anisotropic inherent in 3DCP products [114].

The anisotropy of the 3DCP process is also an influential factor for varying the density of products across layers and printing directions. Such differences in the density of 3DCP materials are formed as a result of layer gaps, voids, and non-uniform compaction [57]. Besides, in the studies [38,105], the 3DCP presented a higher or lower range of density compared to mold-cast based on their mixed materials and fibres. On the other hand, the strength components of cementitious composites are associated with density.

The efforts with the focus on the 3DCP lightweight cementitious materials showed the density’s relationship with the strength properties due to their weight reduction purposes. Fig. 8 illustrates the compressive strength of a study on cast and printed lightweight materials with two densities including E1 and E2 [108]. The values express the reduction of compressive strength in the cases with lower density.

Even though the 3DCP method is linked with changing density, it is a practical method in deterring the decrease of strength components in cementitious composites. In this method, the particular strength factor, which represents the strength parameter divided by density, demonstrated the desired benefit in compressive and tensile strength [57,115]. Ultimately, with all the ups and downs of the 3DCP, it introduces as a disruptive technology among the construction methodologies due to its superiority over traditional methods in customization and eco-friendly performance [116].

3.4. Discussion of section 3

The reviews of this section explored the significance of the 3DCP technology as a breakthrough in fabricating geometrically complex and effective components. Among the 3DCP available methods, extrusion-based is a promising technique in presenting high mechanical properties, while binder jetting provides a system for forming high-resolution structures. These advances mark the versatility of additive manufacturing; however, the method requires specific features of materials to satisfy printability and buildability.

One of the evident trends in 3DCP development is applying sustainable materials that present both challenges and opportunities, where recycled materials are needed to deliver higher ductility by adding fibres. In addition, section 3 reviews special properties of 3DCP construction, including anisotropy, uniform mechanical features, and density alteration. These aspects are critical in the interpretation of crack initiation and propagation. Nonetheless, the 3DCP progress in lightweight materials, strength optimization, and the interlayer connection proves its flexibility.

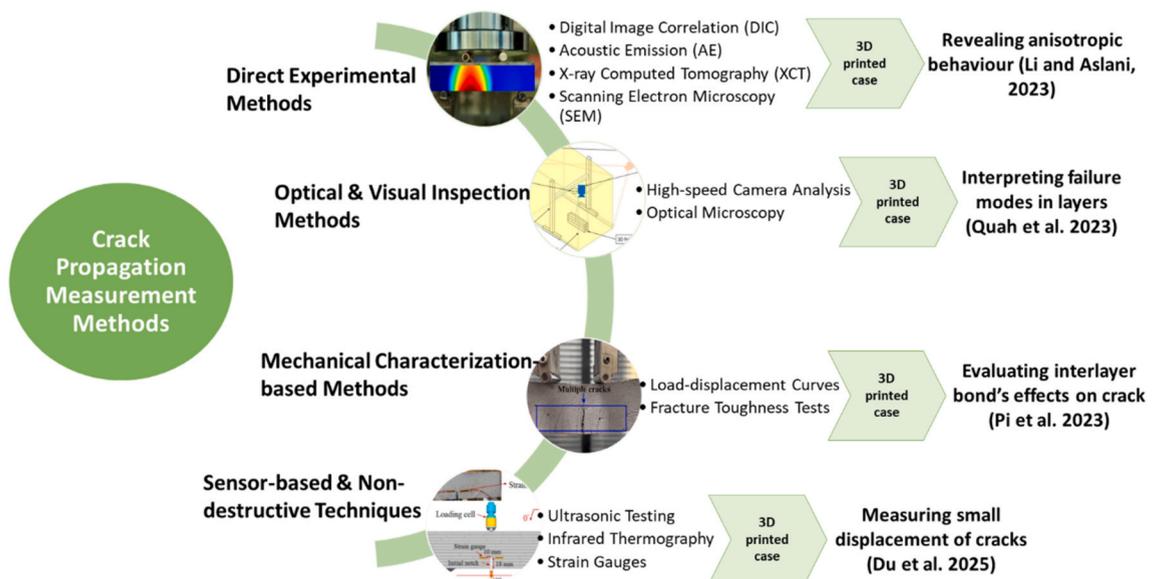


Fig. 9. The crack propagation evaluation methods and related 3D concrete printing applications. References: [19,122–124].

4. Crack mechanisms in 3D printed cementitious composites

The cracking phenomenon in the 3DCP is often evaluated differently from traditional techniques in cementitious composites owing to some effective manufacturing factors like filament deposition and anisotropy [117]. In detail, the 3DCP is implemented through several settings, in which speed, extrusion, and temperature are their imperative parts. These parameters not only impact the morphology of cracks but also shape a sort of crack initiation [118].

Since the crack mechanisms are along with complex alteration and patterns in the cementitious composites, there are several methods including experimental, simulation, and imaging techniques that have interpreted the process [86,119]. Experimental methods in crack evaluation, designing destructive and non-destructive procedures, have a critical role in providing and validating the simulations, however, at the microstructural level, it requires imaging tools like scanning electron microscopy (SEM). Fig. 9 illustrates the crack propagation interpretation methods including 4 main methods, and 11 sub-methods and expresses the benefits of the methods for 3DCP technology.

4.1. Unique cracking patterns in 3D printed structures

The layered construction technique in the 3DCP is a distinguishing point from the traditional casting method in the crack expansion of cementitious composites. The unique anisotropy of layered structure in the 3DCP facilitates higher strength. The anisotropic coefficient (I) (Eq. (1)) [120] was deemed in the 3DCP lightweight concrete project recently [121].

$$I = \frac{\sqrt{(f_x - f_c)^2 + (f_y - f_c)^2 + (f_z - f_c)^2}}{f_c} \quad (1)$$

Where the f_x , f_y , and f_z are the strength (compressive, flexural, and shear strength) of the 3DCP samples and f_c represents cast specimen's strength. According to the findings [121], increasing the time gap between layers enhanced the flexural and compressive anisotropy coefficients by 5 and 3.95, respectively. Therefore, the anisotropic behaviour of the 3DCP can impact crack propagation significantly.

There are some efforts that focus on how the build direction of the 3DCP impresses the crack pattern. In a study [86], the printing directions were defined in X and Y directions, through experiments, they gathered the flexural strength and fracture energy in the X-direction respectively 1.39 and 1.79 times more than the casting results, while these factors for Y-direction were 0.65 and 0.33 times greater. These factors are significant for crack behaviour in cementitious composites as fracture energy is defined as the required energy to generate a unit area of a crack. Hence, higher fracture energy in the printing direction is equal to greater strength against fracture propagation [125].

In addition, the link between printing direction and flexural strength pointed to the anisotropic phenomenon in the 3DCP products, which arises from layered deposition. In this way, optimizing the building direction in large-scale structures is still a challenge, although implementing adjustments through printing is an infrequent option in current systems. In order to deal with the orientation effects of the 3DCP in crack behaviour, anticipating the process, utilizing simulations, adapting printing procedures, and experimental data are feasible solutions.

In cementitious composites, especially ECC materials, tensile strain-hardening behaviour is considerably reliant on the microstructure features. The investigations proved microcracks are inevitable parts of the matrix in both casting and the 3DCP cement-based materials although the sizes of pores are different [44,126]. Consequently, pores that are usually bigger in the cast samples than the 3DCP in the studies, connect to microcracks in a different pattern for a 3D fabricated structure when facing tensile stress [44].

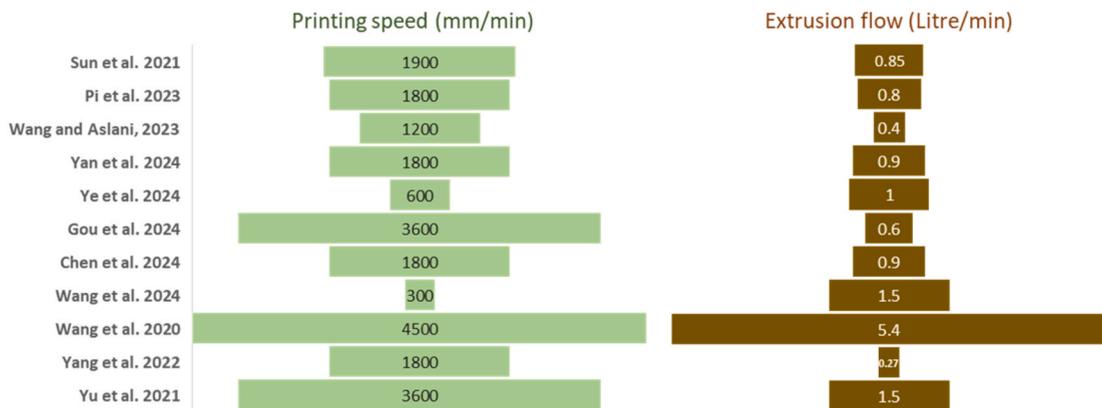


Fig. 10. The range of printing speed and extrusion flow rate of the 3D concrete printing implemented in the previous studies. References: [13,19,91,105,107–109,132,133,135,136].

4.2. Impact of printing parameters on cracking

The printing process has several factors that should be applied in an optimal range to reach the accepted performance and proper mechanical reactions in products. These parameters include printing speed, extrusion flow rate, height of layers, and nozzle size [127]. Fig. 10 illustrates the printing velocity and extrusion flow rate in some 3DCP research that present respectively the average of 2081 mm/min and 1.2 L/min. The optimal range of the printing parameters was linked to crack initiation and propagation in cementitious composites. Based on the experiments [97], moderate printing speed and lower standoff distance (the distance between the nozzle and printing surface) improved the tensile features of the samples.

Regarding the nozzle dimension, efforts proposed empirical correlation [128] and proved nozzle size impacts on the buildability [129]. The correlation with nozzle dimension should be explained in terms of printing speed, layer thickness, and extrusion rate, according to the empirical function analysis. These factors are all important for nozzle design and surface fracture. In the second investigation [129], the outcomes showed increasing the number of layers before failure from 39 to 24 when respectively nozzle diameters were 19 mm–10 mm. They also recommended an area for further research based on the applied stress on the printing head during fabrication and assessing the consequences on the structure strength.

The role of printing parameters on the compaction of layers and creating voids is another critical subject in the 3DCP. In the relationship of porosity and crack expansion, cementitious materials with asymmetric voids are more prone to cracking, thus, higher compaction is connected to a greater strength against fracture propagation [130]. According to the study [131], specimens were acquired from various depths with different compaction, and the tests showed samples with higher compaction indicated greater flexural degree.

In addition, the time interval between printing the layers of the 3DCP materials were presented as an effective feature on the anisotropic behaviours of products, resulting in density and strength properties. Fig. 11 displays the anisotropic coefficient of normal-weight concrete (NWC) and lightweight concrete (LWC) in terms of the time interval of an effort [121]. Three scenarios were implemented consisting of no time interval, a 5-min delay, and combined of the given methods. The bar charts indicate the printing time interval increases the anisotropy calculated by compressive, flexural, and shear strength averages. However, there was a lower range of time interval impact on the LWC materials in contrast to the NWC materials.

4.3. Experimental techniques

Standard experimental methods for the mechanical properties are common and essential for the crack interpretation of 3DCP cementitious composites. Tensile and flexural testing, particularly direct tensile and bending load tests, are useful for 3DCP materials. Fig. 12 shows the specimen dimension and test setting of the uniaxial tensile test (Section A) and three-point bending test (Section B). These tests are typical techniques for assessing tensile strength, fracture toughness, fracture energy, and crack propagation in printing and non-printing directions [132,133].

Through the introduction of innovative materials and structures with 3DCP cementitious materials in years, destructive experiments were the main crack behaviour assessments. Table 3 expresses the studies that used flexural, tensile, and compressive tests utilizing 3DCP cement-based materials or fibre-reinforced cementitious composites. In the flexural test, the four-point bending load method was employed to determine crack expansion in materials with both deflection hardening and multiple cracking [134].

For tensile and compressive tests, they have benefited the crack interpretation in a wide range of projects. Such as tensile strength and cracking measurement with shifting the printing parameters [97], the failure and crack types in interfacial bonding [137], and the cracking as a result of compressive loads on the rubberised ECC [38].

As listed in Table 3, destructive methods have been implemented for a wide spectrum of strength and crack evaluations in cementitious composites. Fig. 13-A to C illustrate the typical presentation of flexural [136], tensile [40], and compressive [127] strength tests. In terms of flexural results, several forms of hollow structures were embedded in the printed materials, with the hollow

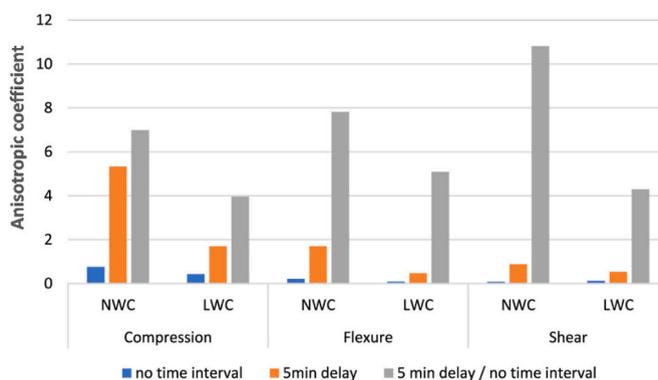


Fig. 11. The anisotropic coefficient of printed samples (normal-weight concrete (NWC) and lightweight concrete (LWC)) in three scenarios including no time interval, 5-min delay, and the combined of the no time and 5-min delay [121].

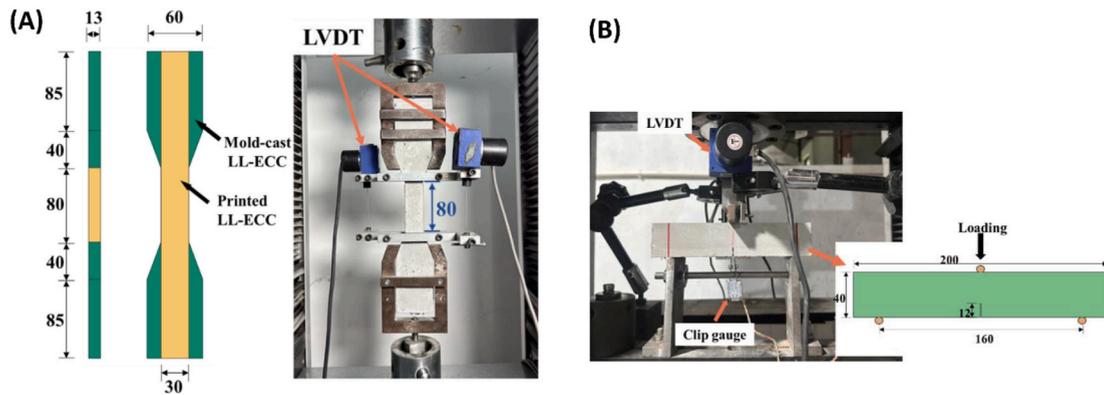


Fig. 12. The test setup for the uniaxial tensile (Section A) and flexural test using three-point bending (Section B) [132].

Table 3

The studies that used flexural, tensile, and compressive tests for crack interpretation in cementitious materials.

Method	Reference	Test type	Tested Material	Crack Evaluation Results
Flexural test	Ding et al. [119]	Four-point bending	Ultra-high performance (UHP) engineered cementitious composites (ECC)	Evaluated ductility index of ordinary and steel reinforced materials; analysed crack width.
	Pi et al. [19]	Three-point bending	ECC materials	Recognized new crack propagation modes: bending cracks leading to filament splitting and focused shear cracks.
	Nguyen-Van et al. [39]	Three-point bending	Steel fibre-reinforced concrete	Identified three crack modes in the bio-inspired Bouligand structures
	Ye et al. [91]	Four-point bending	Self-reinforced lightweight ECC	Introduced fracture expansion in honeycomb-like and rectangular hollow section structures
Tensile Test	Meurer & Classen [149]	Uniaxial tensile test	Hardened cementitious materials	Revealed increasing interval time in printing reduced tensile strength and rose crack expansion
	W. Zhou et al. [97]	Uniaxial tensile test	ECC materials	Presented lower nozzle standoff distance increased tensile strength and reduced cracking
	Q. Liu et al. [150]	Brazilian splitting tensile test	Fibre-reinforced cementitious composites	Exposed increasing nano-CaCO ₃ (NC) in the mix design can fill voids and reduce cracking
	Deng et al. [115]	Uniaxial tensile test	Ultra-lightweight ECC	Observed excellent crack width control in tensile zone with multiple microcracks
Compressive test	Aslani et al. [38]	Uniaxial compressive test	Rubberised ECC	Compared the crack propagation of rubberised ECC with the hybrid of fly ash and rubber in the mix
	Kumar et al. [151]	Uniaxial compressive test	Concrete materials	Proposed crack initiation and expansion limited to translational or depositional interfaces
	Sun et al. [152]	Uniaxial compressive test	Fibre-reinforced concrete	Investigated the printing direction effect on the compressive strength and crack patterns

topology of the triangle and truss experiencing the highest peak bending stress while passing the brittle failure phase.

The tensile strength results (Fig. 13-B) compare two printed samples under tension force with 1 % and 1.5 % fibre contents, respectively B-print and C-print. Both printed specimens reached to strain-hardening step although higher fibre content assisted the specimen to bear more strain, a difference of 2 % in the printed samples. Concerning the compressive results (Fig. 13-C), both 28-day prisms including perpendicular to printing direction (Per) and cast recorded the same maximum compressive strength (around 29 MPa) with different strain ranges. When the loading direction was parallel to the printing direction (Par), the specimen showed more brittle behaviours in failure and touched a lower maximum compressive stress (around 23 MPa).

As presented in the cases with destructive methods, higher fibre content contributed to the strain-hardening phenomenon in tension, whereas compressive responses depend on loading direction in the 3DCP. In detail, improved tensile factor and weaker compressive feature are respectively caused by fibre bridging and interlayer bond, leading to a challenge in the mechanical performance of printed structures. If a system balances fibre content, mix design, and printing factors, the outcome could address the compressive reduction.

Non-destructive experimental methods like X-ray tomography and ultrasonic tools are other effective techniques for analyzing internal cracks of cementitious composites. Fig. 14 illustrates the X-ray computed tomography (X-ray CT) results in the bulk and interlayer regions, which portray the pores in the matrix of cementitious composites [138]. The data acquired from the X-ray CT can pass threshold, segmentation, and 3D structure reconstruction steps to provide detailed spatial distribution and crack initiation spots [139]. Moreover, the application of X-ray CT was proved in post-cracking characteristics in the ECC materials, which are essential in modern material analysis [140].

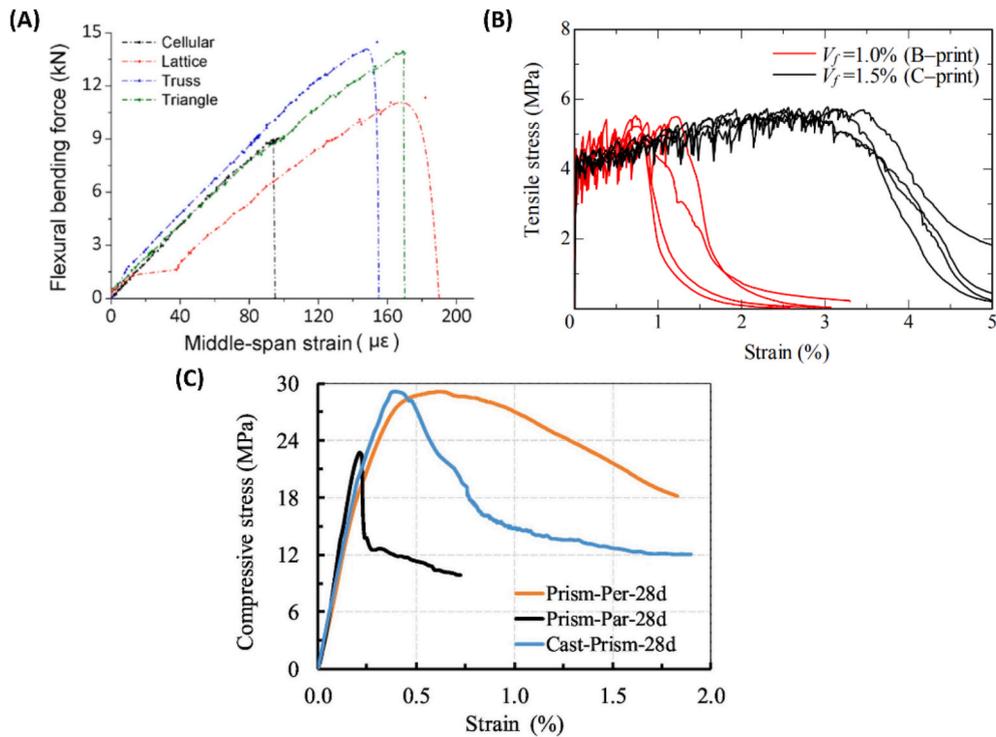


Fig. 13. The results of flexural, tensile, and compressive strength tests respectively in sections A, B, and C [40,127,136].

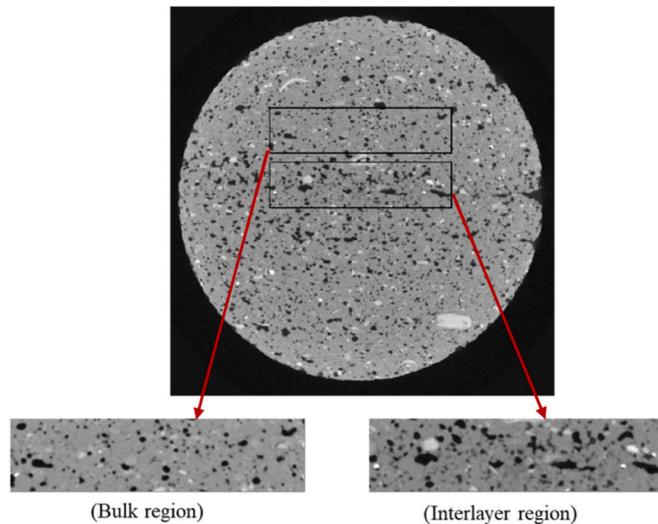


Fig. 14. The results of X-ray computed tomography (X-ray CT) in the bulk and interlayer regions of a case with cementitious composites [138].

The presence of fibres and fine aggregates in 3DCP cementitious composites was investigated for crack analysis using the X-ray CT method. These additives are so significant in crack formation because of controlling interlayer bonds, pore distribution, and crack initiation paths [141]. The strain and stress distributions acquired from X-ray CT in 3DCP composites are other critical components in crack evaluation. As regards when multi-directional structures are incorporated in cementitious composites, the results of X-ray CT revealed the reduction of crack growth in reinforced samples compared to regular ones because of mitigating the localised strain [142].

In addition, the crack behaviour and failure mechanism are deeply investigated with digital image correlation (DIC), which prepares real-time monitoring of crack growth. The DIC has been used widely such as fatigue crack propagation utilizing crack opening displacement [143], crack expansion in different stress distributions [122], and crack interpretation in complex structures [144]. The combination of destructive methods with non-destructive or imaging techniques highlighted a comprehensive insight into crack

propagation, aiding in the analysis of crack formation [145]. Therefore, increasing their hybrid methods and resolution could be a critical option for improving 3DCP items that break in the future.

Since the DIC method delivers a precise strain distribution, it has been used to analyze crack development from different points of view. The DIC interpretations presented several properties of 3DCP fibre-reinforced cementitious composites like fibre bridging effects [146], printing pattern influence [147], and the relationship of displacement and crack opening [148]. Their results proposed that the DIC imaging not only tracked micro- and macro-cracks characteristics such as length and depth but also provided calibration sources for establishing fracture mechanics models.

Fig. 15 shows the DIC outcomes of a study [153] that used the three-point bending load on a 3DCP fibre-reinforced cementitious samples before (left side) and through crack propagation (right side). Before the crack expansion, the loading process made a uniform stress distribution in almost all areas of the sample while some small stress concentrations created compressive strain growth in loading points. In the crack expansion step (Fig. 15, right side), a considerable tensile area, a red zone with a normal Lagrange strain of 0.0016 (ϵ), was formed in the lower section of the mid-span on the sample. The given zone exhibited crack propagation when the tensile stress passed the ultimate tensile strength, leading to a brittle failure.

4.4. Numerical simulation approaches

Numerical simulations are practical techniques for demonstrating special characteristics of the 3DCP cementitious composites e.g. the stress distribution in layers, crack initiations in cohesive interfaces, the crack pattern for various interval times, crack propagation in complex designs, and damage analysis [130]. Fig. 16 depicts a flowchart of standard numerical methods for modelling cementitious composites in three major techniques, as well as accompanying sub-sections and studies. However, all of the methods have not been used for the 3DCP cementitious composites, they can present feasible solutions for the analysis of 3DCP materials.

Finite element modelling (FEM) and discrete element methods (DEM) are two popular simulation procedures that respectively discretise the structure into small elements and simulate an assembly of discrete particles related to each other for computation [65]. The FEM was implemented in the 3DCP cement-based materials for estimating displacement and crack distribution with cohesive elements in layers of the ECC [154] and predicting crack patterns using interfacial bonding [86].

The DEM simulations satisfied additional requirements for identifying 3DCP materials by taking into account dynamic mechanical properties and microscopic crack initiation [155]. According to their definitions, the DEM and FEM stand for different computing mindsets, the DEM's crack propagation acquires from particle interaction while the FEM interprets the cracks in a continuous structure. Therefore, the DEM is suitable for mesoscale simulation and based on the purpose of the crack evaluation scale, the method should be selected in the cementitious composites [136,144].

Since the crack interpretation of fabricated materials using the 3DCP technology requires to be simulated at micro- and macro-levels, methods designed for one of them could not sufficiently deal with the process. Multi-scale techniques in the crack behaviour are feasible tools for the lack of analysis in both microstructural level and macro-scale performance. In this way, the study [156] proposed a double-scale model that is ideal for the failure prediction in fibre-reinforced cementitious composites in both cracking and fibre bridging phenomena. Despite the diversity of numerical methods, they should be validated through experimental and microstructural investigations.

4.5. Microstructural analysis

The process of 3DCP has some characteristics that influence the cement's structure in micro-scale and trigger the crack initiation. The pore distribution is associated with the fabricating and printing parameters and the hydration products contribute to the mix design, admixture types, and curing conditions are influential factors in the crack propagation on the micro level [157]. In the chemical method to improving the interlayer strength of the 3DCP layers, it was demonstrated that using polymers that link the dehydrated particles in the matrix with hydration products strengthens bonding [158]. The superplasticizer-based binder is one of the recommended adhesive agents.

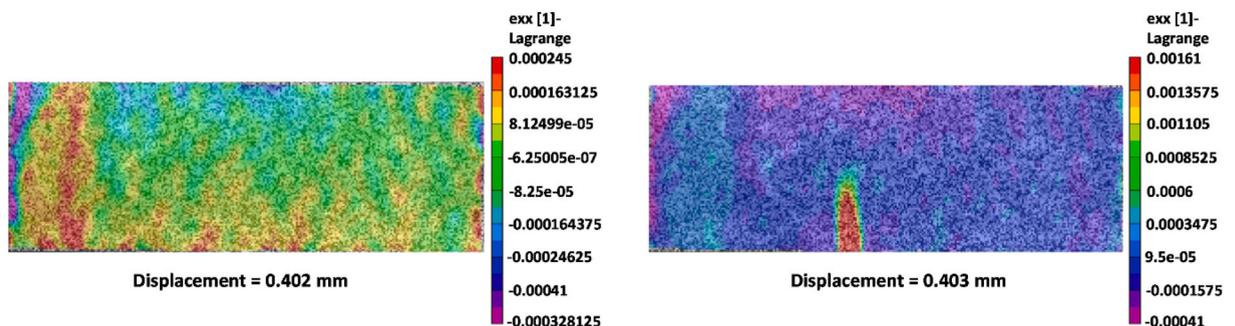


Fig. 15. The DIC imaging results of three-point bending load tests on 3D printed cementitious composites before (left side) and through crack propagation (right side) [153].

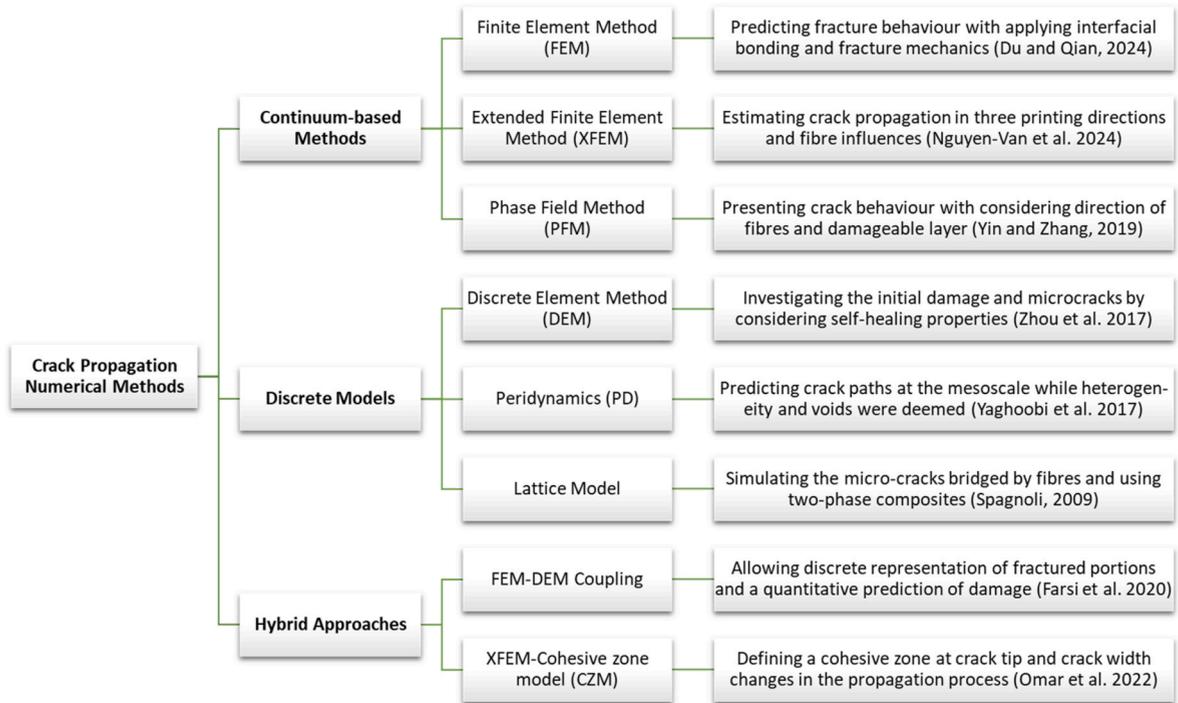


Fig. 16. The flowchart of common numerical techniques for simulating the crack propagation in cementitious composites. References: [86,162–168].

In addition to the hydration products, the study of interfacial transition zones (ITZ) between the 3DCP layers is a common microstructural determination for crack interpretation. Scanning electron microscopy (SEM) is a valuable tool for the analysis of the crack behaviour in printed structures, paving the path for novel design and improved performance [103,159]. The interpretation of pores is one of the feasible benefits of the SEM for crack initiation evaluation, where the shrinkage phenomenon or other effective properties form defects under pores transforms [160]. Adding X-ray CT to the interpretation system enables scholars to find internal defects in 3D, which reveal possible initiatives to control crack initiation spots [161].

Fig. 17 illustrates the scanning electron microscopy (SEM) results for interfacial transition zones (ITZ) analysis in the matrix (Section A) [169] and the hydration products around the fibre (Section B) [170] in the fibre-reinforced cementitious composites. This advanced method showed high-resolution pictures that enhanced insight into the microstructure and crack mechanisms, leading to an optimized printing procedure.

The SEM outcomes are also precious resources for investigating the role of aggregates in different scales and shapes that are added

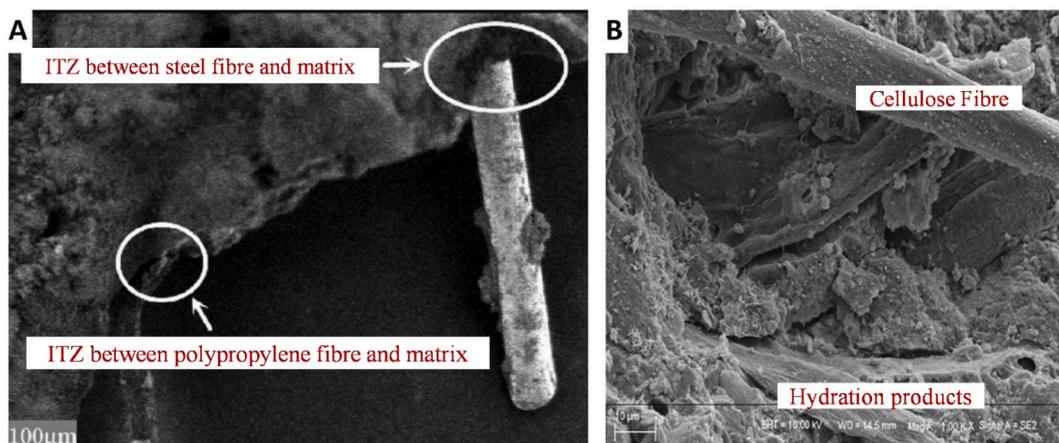


Fig. 17. The results of scanning electron microscopy (SEM) for interfacial transition zones (ITZ) (Section A) and hydration products around the fibre (Section B) [169,170].

to 3DCP cementitious mixtures for special purposes. In this way, the SEM data in the study [171] proved the growth of flexural strength in the 3DCP layers of cementitious composites due to higher interlayer bonds. The improved interlayer strength was visible in a denser microstructure and higher material integrity.

4.6. Discussion of section 4

Section 4 investigates the efforts in crack mechanisms of 3DCP materials and distinguishes their crack behaviours from the traditional casting method due to the unique fabrication and layered deposition. In terms of experimental methods, destructive and non-destructive techniques have indicated detailed information about failure mechanisms. Regarding numerical simulation methods, FEM and DEM techniques allow the incorporation of prediction scenarios in crack analyses with stress distribution and crack propagation patterns.

In the following, the review focuses on the remained challenges of the 3DCP process when fine-tuned printing parameters influence on mechanical reaction of materials. In addition, despite the fact that experimental and imaging techniques present precise insights into printed materials, integration of simulations and microstructural data is required to make a universal framework. In this way, optimization methods can deliver printing factors that deal effectively with anisotropy, compaction, and porosity. One of the possible methods is implementing hybrid testing approaches based on loading tests and imaging techniques, which generate comprehensive data for simulation calibration. These efforts are valuable for crack evaluation and improving the fracture resistance of future 3DCP materials.

5. Influence of fibre reinforcement on crack behaviour

Fibre reinforcement has been accepted for its capability to alleviate mechanical properties, especially tensile strength and ductility, marking more strength against cracking [172]. These benefits of fibres are turned into superior characteristics when they are implemented through the 3DCP technology due to the effective direction and stacking of layers [173]. The effect of fibres is also contributed to the selection of fibre types from a wide spectrum with their specific properties. For instance, polymeric fibres were introduced as flexible and effective in crack resistance [174].

Furthermore, fibres geometry is a key factor in tailoring 3DCP cement-based materials that serve not only a higher control on the crack expansion but also printable mix design due to the difficulties that have been seen in fabricating longer fibres [130]. Therefore, the synergy of the fibre-reinforced method and 3DCP approaches can produce a one-of-a-kind performance if their main factors are ideal and directed towards the desired structure.

5.1. Mechanisms of crack bridging by fibres

The interactions of fibres and matrix, when cracks are growing in cementitious composites, are pivotal in improving the overall toughness. Incorporating fibres in cement-based products was evaluated in flexural toughness [175], ductility in post-cracking [176], and high temperature [177]. The reason behind the effective fibre-matrix interaction is the different interfacial characteristics between fibre and cement matrix that create low porosity resulting in considerable compound with hydrated cement and a compacted microstructure [178]. However, several treatments for the fibre-matrix interactions like changing surface [179] or nano-carbon fibre [180] have been applied, the basic fibre applications showed more crack resistance than the ordinary cementitious composites.

The fibre functions are also contributed to the increase of tensile strength and fracture toughness because of two mechanisms made up of the stress distribution and energy absorption [181]. As follows, the energy consumption was investigated in steel fibre-reinforced

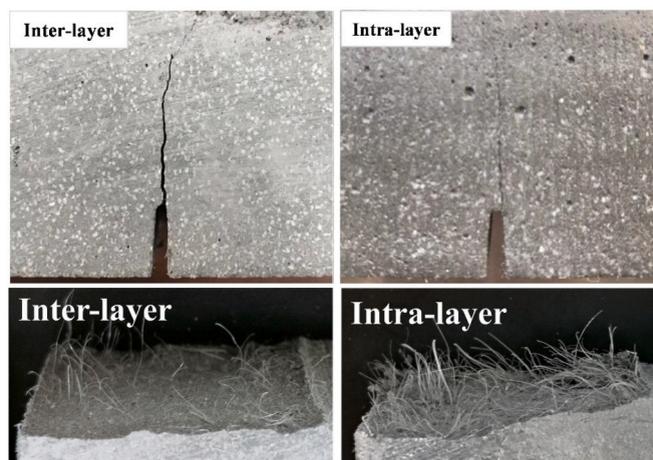


Fig. 18. The microstructural analysis of the inter-layer and intra-layer spots in two cases of fibre-reinforced cementitious composites [97,108].

concrete with the bending load [182], and their significant fracture energy was pointed out as improved plastic behaviour. However, poor stress redistribution due to unmatched factors, such as a low extrusion range, generates non-uniform fibre orientation and localization. These challenges in the 3DCP products could be handled using a rheology adapter and optimized nozzle design.

Besides the toughness and energy absorption, fibre networks can inhibit crack expansion and widen to different extents due to the fibre bridging properties. Interfacial bonding is created and tensile strength is increased by filling in the spaces between deposited layers [183]. According to research [97,108], fibre bridging greatly influences the behaviour of cracks and even creates distinct crack patterns in 3DCP cementitious composites both intra-layer and inter-layer (between and within layers). Fig. 18 illustrates the crack propagation of inter- and intra-layers of two fibre-reinforced studies, where a weaker fibre-bridging effect in inter-layer facilitated the rapid expansion. In the high-quality images of inside inter- and intra-layers of Fig. 18, the fracture surfaces show the quantity and position of fibres that direct stress redistribution concentrated at the crack tip and ultimately follow different crack patterns.

5.2. Impact of fibre types (steel, synthetic, natural, etc.)

Since the advent of fibre incorporation in concrete and cementitious composites, several fibres with special aims, including crack reduction, have been involved in the mix design of materials [184]. These fibres were then developed and used for 3DCP technology in synthetic and sustainable applications, as well as a range of materials with an efficient mechanical reaction [145]. Table 4 shows the different types of fibres that were employed in the 3DCP cement-based materials and their practical influence on the crack mitigating process.

Steel fibres are classical fibres that are defined by their crack resistance and mechanical durability. Proper distribution of steel fibres in the 3DCP process was reported for shifting failure mode under static and dynamic loadings in cementitious composites [185]. Regarding the carbon fibres, despite their common usage as conductive fillers, they demonstrated an accepted mechanical as well as high load-bearing capacity in lightweight structures [135]. When carbon fibres assist in absorbing high tensile stresses, complex structures fabricated with the 3DCP harness the cracking [186]. Carbon fibres can be further modified by lightweight and complex constructions, but steel fibres offer superior flexural strength and loading capacity [187].

For the 3DCP materials, a variety of fibres were utilized, including synthetic fibres like polyvinyl alcohol (PVA) [107] and polyethylene (PE) [103], and natural fibres such as cellulose fibres [52]. Their experiments on synthetic or polymer-based and natural fibres indicated the enhancement of flexural and tensile strength.

Even though the PVA and PP fibres were feasible in crack controlling of the 3DCP cement-based products, the PVA and PP fibres' performance was respectively ideal for interlayer bonding and plastic shrinkage cracking [152,188]. Consequently, some hybrid fibre systems have been created that not only serve balanced mechanical properties but also optimize crack resistance. For instance, in a study combined glass and PP fibres [189], proportion rates of half/half and unbalanced proportions of the fibres were tried, and the outcomes revealed 75/25 % of the PP to glass fibres, tensile strength, and plastic behaviour were rose significantly.

5.3. Influence of fibre characteristics (length, diameter, aspect ratio)

The physical properties of fibres have been tested in various products of the 3DCP cementitious composites due to their outstanding effects on mechanical responses. Fibres with different lengths were assessed [198,199] and their results presented the crucial role of the length factor in fibre bridging. If fibres are incorporated into a combined method for the 3DCP procedure, their optimal length should be deemed to meet the flowability, buildability, and crack resistance. According to research [200], when the PE, steel, and cellulose fibres with a respective length of 18 mm, 13 mm, 300 m were applied in the ECC mixture, their optimal range of length led the products had the balanced printability and interlayer adhesion as well as superior durability.

The aspect ratio, which includes both length and diameter, is an important feature in the geometrical properties of fibres, and comparative studies have been conducted to investigate its impact. Although aspect ratio has not been fully investigated in the 3DCP

Table 4

Some fibres that were utilized in the 3DCP cementitious composites and their effects on the crack mitigating process.

Reference(s)	Fibre type	Cementitious composite type	Crack mitigating impacts
Liu et al.; Zhang & Aslani [190,191]	Polyvinyl alcohol (PVA)	Engineered cementitious composite (ECC); reinforced concrete	Flexural and compressive strength increased; bridged cracks to reduce material explosion; enhanced crack initiation toughness.
Ding et al.; Nasr et al.; Xiao et al. [43,103,192]	Polyethylene (PE)	Reinforced concrete	Crack propagation resistance improved; made microcracks to avoid cracks in layers; increased multiple cracking to control propagating along the interface.
Pan et al.; Van Der Putten et al. [193,194]	Polypropylene (PP)	Reinforced concrete and cementitious composites	Shrinkage cracking potential reduced; contributed to strain-hardening behaviour; improved ductility for resisting cracks.
Bos et al. [195]	Steel fibre	Reinforced concrete	Macro-crack propagation delayed; increased fracture toughness.
Igbokwe et al.; Kilic et al. [52,196]	Cellulose fibre	Reinforced cementitious composites	Fibre bridging the cement matrix rose and crack propagation suppressed; microscopic cracks healed.
Rutzen et al. [186]	Carbon fibre	Reinforced cementitious composites	Crack width limited with microcrack; energy dissipated under loading to control cracks.
R. Yang et al.; Zhang et al. [139,197]	Glass fibre	Reinforced cementitious composites	Pre-peak mechanical performance improved; deformation restricted by energy absorption; interlayer porosity and cracking decreased.

technology, the extrusion process with glass and PVA fibres [201] and the flexural behaviours [202] applying different aspect ratios were analysed. The study with PVA and glass fibres proved the growth of bulk yield strength in a higher aspect ratio.

Fig. 19 depicts [202] the applied load and flexural stress versus the deflection in different fibres in shapes and aspect ratios. Including the short straight (SS, aspect ratio: 65), medium straight (SM, 97.5), long straight (SL, 100), long hooked (HL, 80), and long twisted (TL, 100) fibres. Based on Fig. 19, straight fibres were measured with higher flexural stress than twisted ones. On top of that, enhancing the straight fibres' aspect ratio was equal to greater flexural and loading numbers and resulted in higher control on the crack expansion. The improved flexural strength of the given study was achieved in straight fibres by stronger fibre bridging and delayed crack expansion. Nevertheless, in on-site fibre-reinforced cementitious structures, twisted fibres generated through non-uniform loading result in decreased load transferring features. For tackling this weakness point in fibre-reinforced 3DCP, fibre geometry should be adapted with the required bond strength, as well as combining fibres with straight and shaped forms.

In details of fibres physical effects on the crack behaviours, their degree of slenderness and stiffness were introduced as significant parameters [139]. If fibres are incorporated with larger slenderness in the cementitious composites, they are some paths for more air voids in the matrix of materials, and interlayer pore structures are related to crack propagation [203]. There is still a lack of comprehensive analyses of fibre characteristics on the 3DCP procedure, directing to optimal integration of fibres for fabricating process in cement-based products.

5.4. Synergistic and distribution effects of fibre in 3D concrete printing

The orientation of fibres within the manufacturing method of the 3DCP, especially in the extrusion-based manner, is interconnected with mechanical features of composite materials. Through the experiments of the 3DCP materials, it was asserted that the fibre orientation is closely associated with fibre number [198], load transfer distance [174], and fibre bridging [204]. Fig. 20 illustrates the results of the study on the load transfer distance [174] in three cases including cast and two 3DCP's cases with 20 mm and 8 mm nozzle sizes. As shown in Fig. 20, the 3DCP-20 mm case supplied about the same amount of load transfer distance as the cast case, however the 3DCP materials had a reduced crack spacing. Therefore, the outcomes proposed the fibre orientation influences of the 3DCP materials on the crack behaviours and overall tensile performance.

The 3DCP products can benefit the structures with tailoring the load bearing in a particular side employing an effective fibre orientation. The fibre orientation was deemed in a binder jetting 3DCP [205] when they tried some printing directions. Their research revealed a special direction that had 60 % more strength than the other directions and attracted more fibres. Besides the strength, the amount of energy distribution in the crack opening process was recorded as a factor associated with fibre orientation [206].

Proper fibre dispersion is also an important indicator in the examination of fibre-reinforced materials made with 3DCP. If the mixing process, amount of water content, the geometry of the structure, printing parameters, nozzle size, and fibre selection are applied precisely, the desired fibre distribution will be achieved [207,208]. Fibres distribution index is different based on their type and the production method. The milled carbon fibre was reported [209] as a challenging fibre for implementing adequate dispersion due to its natural properties. However, adding silica fume during the mixing process of milled carbon fibre was presented as an approach for enhancing its dispersion [210].

In addition to the dispersion, the clustering of fibres in the fibre-reinforced composites has introduced the cause for the localized stress points, thereby increasing crack initiation targets [211]. Fig. 21 illustrates both mentioned factors, local fibre content (V_f) and fibre dispersion coefficient (α_f), in the normal and printed ECC cases [44]. The cases indicated the printed specimens had a lower percentage of the localized fibres while exhibiting higher distribution compared to the normal ECC. The uniform distribution of the fibre-reinforced ECC strengthens a vast area of the matrix against fibre initiation and propagation.

5.5. Discussion of section 5

Involving fibres in the 3DCP materials produces transformative paths in crack propagation due to hybridizing the benefits of fibre-reinforced concrete with a layer-by-layer digitalized process. However, fibres enhance the mechanical strength in traditional casting systems, extrusion-based 3DCP process directs fibres at an angle that empowers interfacial bonding. Concerning fibre types and geometrical properties, they influence materials not only their mechanical reaction as a result of some factors such as stress distribution, but also fracture characteristics.

In addition, studies have shown that the ideal 3DCP process requires both fibre features, including length, diameter, and aspect ratio, and the flowability of material mixture in optimal ranges. As regards, longer fibres tend to increase flexural strength while reducing the flowability of the mixture. Achieving the desired fibre characteristics alongside the printing parameters, such as nozzle size and printing speed, is still challenges that lead to clustering or uniform distribution of fibres. All in all, the effectiveness of fibres in future 3DCP materials depends on their tailored integration by considering extrusion requirements in order to gain long-term durability.

6. Overall discussion

The review has shown that the characteristics of cracks in the 3DCP cementitious composites are correlated with printing parameters, fibre features, and material properties. Across the sections of the review, unique properties of 3DCP, such as anisotropy and strain redistribution, which are respectively generated by the layer-by-layer deposition and integration of fibres, were explained.

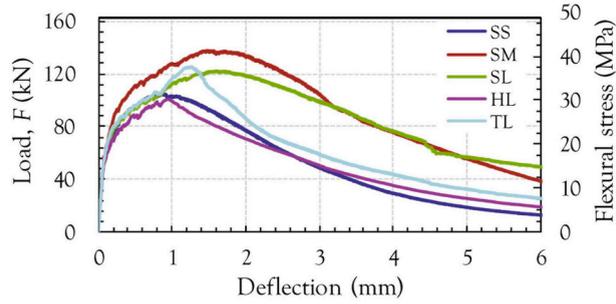


Fig. 19. The implemented load and flexural stress versus the deflation in different fibres, shapes, and aspect ratios. Fibres were short straight (SS, aspect ratio: 65), medium straight (SM, 97.5), long straight (SL, 100), long hooked (HL, 80), and long twisted (TL, 100) fibres [202].

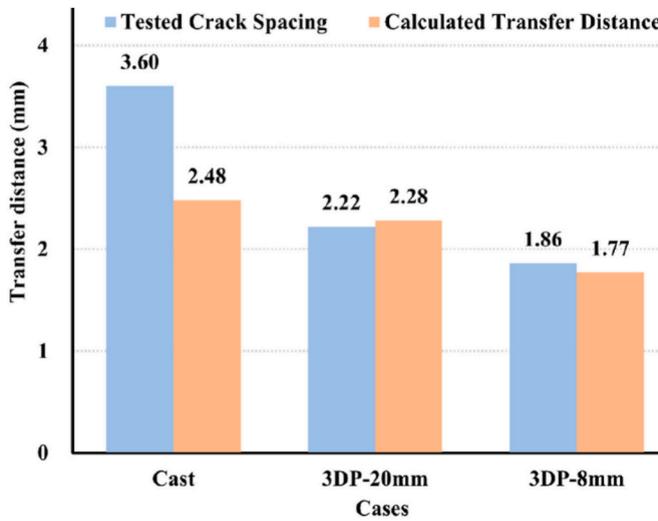


Fig. 20. The outcomes of load transfer distance and crack spacing in three cases including the casting method, 3D printed with 20 mm nozzle, and 3D printed with 8 mm nozzle [174].

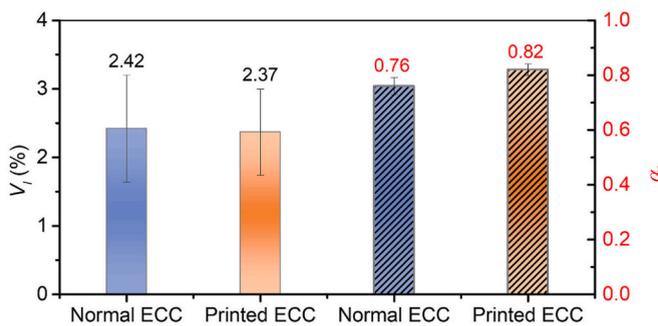


Fig. 21. The results of local fibre content (V_f) and fibre dispersion coefficient (α_f) in the normal and printed ECC samples [44].

Despite the fact that fibre-reinforcement benefits the extrusion-based 3DCP with superior strength when fibres are directed efficiently, an optimization that covers materials and process remains essential due to the complex interplay of parameters.

Regarding the practical aspects of the 3DCP, studies have confirmed implications for structural designs and the autonomous construction process. Fibre reinforcement is a proper method for developing materials with particular characteristics, such as lightweight and high-strength elements for house construction and prefabricated sections used in bridges. Furthermore, there are some feasible opportunities to contribute to effective fibre orientation of the 3DCP, which allow the process to tailor the crack resistance in the areas with localised stress.

Looking forward, studies can be conducted in fibre-reinforcement applications with additive and lightweight materials in specific

geometries to meet the buildability, printability, and sustainability of the 3DCP process. Moreover, since the crack propagation is linked with fibre orientation and interlayer strength in the 3DCP, predictive models that interpret the given interactions can improve structural integrity. Clockwise to modern technology, systems with hybrid fibres and machine learning deserve to be set as the main purposes of future development of the 3DCP workflows. Such efforts, alongside focusing on implementing laboratory-scale projects in field-scale, could optimize mix designs and materials properties, and fill the gap between pilot construction and on-site projects.

7. Conclusion and future directions

The undeniable potential of cementitious composites has led to the improvement in construction materials due to their creative products in combination with other substances such as fibre-reinforced cementitious composites. The 3DCP technology is deemed a revolutionary procedure with significant influence on the digitalized manufacturing process, which incorporates cementitious composites in various applications. The combination of 3DCP technology and fibre-reinforced composites produces materials with high mechanical qualities and complex designs in a time-consuming process. Despite all the advantages, cracking is a crucial defect that contributes to the performance and durability of the 3DCP products.

This review highlighted the significance of interpreting the crack behaviours in innovative fibre-reinforced 3DCP composites. Key findings in the investigation of crack patterns through the 3DCP structures and the fibre reinforcement's proportion on the crack resistance were introduced. The summarized outcomes are elaborated on below.

- Crack initiation and propagation in traditional cement-based materials are primarily associated with weak interfacial zones and loading-induced stress conditions, respectively.
- Limitations of conventional crack mitigation techniques, such as susceptibility to corrosion, underscore the need for fibre-reinforced 3D concrete printing (3DCP) technology.
- Advances in the 3DCP technology support the creation of complex geometries and improved crack resistance; however, challenges related to scalability and regulatory acceptance remain.
- In comparing crack propagation in extrusion-based and binder jetting 3DCP methods, extrusion printing tends to produce stronger interlayer bonds, whereas the porous structure of binder jetting makes it more prone to cracking.
- The average spread diameters representing the lower and upper bounds for the flowability of 3DCP mix designs were 146 mm and 182 mm, respectively, indicating good printability and controlled cracking behaviour.
- Although 3DCP enables customised aggregates, in order to stop cracks from spreading, issues with intrinsic anisotropy, poor interlayer bonding, and inconsistent mechanical performance must be resolved.
- Materials printed via 3DCP with controlled anisotropic coefficients and specific build orientations demonstrated improvements in flexural strength by factors of 5 and 1.39, respectively, resulting in varied crack patterns.
- Key printing parameters, such as speed, extrusion rate, layer height, and nozzle size, significantly affect crack behaviour. In the studies analysed, average printing speed and extrusion rate were 2081 mm/min and 1.2 L/min, respectively.
- A comprehensive investigation of cracking in 3DCP materials can be achieved through a combination of experimental, numerical, and microstructural analyses. Experimental and simulation methods provide complementary data for crack measurement and validation, while micro-level assessments are essential for evaluating pore distribution, hydration products, and interfacial transition zones (ITZ). A hybrid approach combining three-point bending, finite element modelling (FEM), and scanning electron microscopy (SEM) offers in-depth insight into crack behaviour.
- Fibre reinforcement in cementitious composites improves fracture toughness, energy absorption, and fibre bridging. These properties can be significantly enhanced by optimizing fibre orientation and stacking.
- Steel, polyvinyl alcohol (PVA), and polypropylene (PP) fibres are suitable for high load-bearing capacity, improved interlayer bonding, and control of plastic shrinkage during the 3DCP process, respectively.
- 3DCP enables optimized fibre orientation, which improves fibre distribution, load transfer efficiency, and fibre bridging, all of which influence crack propagation behaviour.
- Higher distribution and lower localized conditions of fibres in the 3DCP structures grow the crack strength and reduce the possible crack initiation spots.

The present research is limited by the challenges in replicating and adapting to real on-site conditions. In addition, there is a need for extensive studies on the long-term durability, structural integrity, and environmental performance of large-scale 3D-printed structures. Integrating fibre-reinforcement solutions, notably the combination of diverse fibre types while optimizing aspect ratios, volume fractions, and orientation, can greatly improve fracture resistance in the future. Moreover, optimizing 3DCP parameters such as printing speed, extrusion rate, layer height, and nozzle geometry in tandem with mix design can further enhance performance.

Emerging approaches involving the hybridization of smart materials (e.g., shape memory alloys, self-healing agents, or piezoelectric additives) with computationally optimized 3DCP architectures provide promising avenues for proactive crack control. Advanced modelling techniques, including AI-driven optimization and physics-informed machine learning, can support the prediction of crack initiation and propagation at both macro and micro scales. High-resolution microstructural analysis, such as through X-ray computed tomography and SEM imaging, should be coupled with numerical simulations to provide more accurate crack pattern predictions.

Furthermore, advancements in fibre reinforcement combining natural fibres (e.g., hemp, flax, sisal) with synthetic fibres (e.g., PVA, PP, steel), while tailoring their geometrical properties through AI-based generative design tools, can improve sustainability,

mechanical strength, and energy absorption of printed structures. These innovations not only enhance material efficiency and resilience but also align with green building goals and circular construction principles.

CRedit authorship contribution statement

Mohammad Reza Delavar: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Farhad Aslani:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Tim Sercombe:** Writing – review & editing, Validation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

- [1] V.C. Li, C.K. Leung, Steady-state and multiple cracking of short random fiber composites, *J. Eng. Mech.* 118 (11) (1992) 2246–2264.
- [2] F. Hamidi, F. Aslani, Additive manufacturing of cementitious composites: materials, methods, potentials, and challenges, *Constr. Build. Mater.* 218 (2019) 582–609.
- [3] M. Yang, et al., Advancing environmental sustainability in construction through innovative low-carbon, high-performance cement-based composites: a review, *Mater. Today Sustain.* 26 (2024) 100712.
- [4] P. Zhang, et al., Fracture models and effect of fibers on fracture properties of cementitious composites—A review, *Materials* 13 (23) (2020) 5495.
- [5] F. Wittmann, Crack formation and fracture energy of normal and high strength concrete, *Sadhana* 27 (4) (2002) 413–423.
- [6] S. Fallah, M. Nematzadeh, Mechanical properties and durability of high-strength concrete containing macro-polymeric and polypropylene fibers with nano-silica and silica fume, *Constr. Build. Mater.* 132 (2017) 170–187.
- [7] J.-H.J. Kim, et al., Effects of the geometry of recycled PET fiber reinforcement on shrinkage cracking of cement-based composites, *Compos. B Eng.* 39 (3) (2008) 442–450.
- [8] J. Choo, et al., Modeling and optimizing the effect of 3D printed origami bubble aggregate on the mechanical and deformation properties of rubberized ECC, *Buildings* 12 (12) (2022) 2201.
- [9] P. Cheng, et al., 3D printed continuous fiber reinforced composite lightweight structures: a review and outlook, *Compos. B Eng.* 250 (2023) 110450.
- [10] W. Hufenbach, et al., The effect of temperature on mechanical properties and failure behaviour of hybrid yarn textile-reinforced thermoplastics, *Mater. Des.* 32 (8–9) (2011) 4278–4288.
- [11] P.W. Beaumont, On the problems of cracking and the question of structural integrity of engineering composite materials, *Appl. Compos. Mater.* 21 (2014) 5–43.
- [12] B.-T. Huang, et al., Static and fatigue performance of reinforced concrete beam strengthened with strain-hardening fiber-reinforced cementitious composite, *Eng. Struct.* 199 (2019) 109576.
- [13] J. Yu, et al., Research on damage and deterioration of fiber concrete under acid rain environment based on GM (1, 1)-Markov, *Materials* 14 (21) (2021) 6326.
- [14] M. Szelag, Evaluation of cracking patterns in cement composites—From basics to advances: a review, *Materials* 13 (11) (2020) 2490.
- [15] S.-W. Kim, et al., Crack damage mitigation and shear behavior of shear-dominant reinforced concrete beams repaired with strain-hardening cement-based composite, *Compos. B Eng.* 79 (2015) 6–19.
- [16] Y. Wan, et al., Effect of shrinkage reducing agent and steel fiber on the fluidity and cracking performance of ultra-high performance concrete, *Fluid Dynam. Mater. Process.* 20 (9) (2024).
- [17] H. Mihashi, S.F.U. Ahmed, A. Kobayakawa, Corrosion of reinforcing steel in fiber reinforced cementitious composites, *J. Adv. Concr. Technol.* 9 (2) (2011) 159–167.
- [18] S. Abdallah, M. Fan, D.W. Rees, Bonding mechanisms and strength of steel fiber-reinforced cementitious composites: overview, *J. Mater. Civ. Eng.* 30 (3) (2018) 04018001.
- [19] Y. Pi, et al., Crack propagation and failure mechanism of 3D printing engineered cementitious composites (3DP-ECC) under bending loads, *Constr. Build. Mater.* 408 (2023) 133809.
- [20] S. Hou, et al., A review of 3D printed concrete: performance requirements, testing measurements and mix design, *Constr. Build. Mater.* 273 (2021) 121745.
- [21] Y.W.D. Tay, et al., 3D printing trends in building and construction industry: a review, *Virtual Phys. Prototyp.* 12 (3) (2017) 261–276.
- [22] Y. Zhang, et al., Comparison of printability and mechanical properties of rigid and flexible fiber-reinforced 3D printed cement-based materials, *Constr. Build. Mater.* 400 (2023) 132750.
- [23] M.K. Mohan, et al., Extrusion-based concrete 3D printing from a material perspective: a state-of-the-art review, *Cement Concr. Compos.* 115 (2021) 103855.
- [24] G. Ma, Z. Li, L. Wang, Printable properties of cementitious material containing copper tailings for extrusion based 3D printing, *Constr. Build. Mater.* 162 (2018) 613–627.
- [25] H.-Q. Sun, et al., Mechanical and microstructural characterization of interlayer bonding in multi-material 3D-Printed concrete, *Cement Concr. Compos.* 165 (2026) 106308.
- [26] G. Ma, et al., Mechanical improvement of basalt fiber reinforced cementitious material for binder jetting 3D printing, *Addit. Manuf.* 100 (2025) 104688.
- [27] P. Shakor, et al., Effects of different orientation angle, size, surface roughness, and heat curing on mechanical behavior of 3D printed cement mortar with/without glass fiber in powder-based 3DP, *3D Print. Addit. Manuf.* 10 (2) (2023) 330–355.
- [28] R.K. Dhir, A.W. Yap, Superplasticized flowing concrete: strength and deformation properties, *Mag. Concr. Res.* 36 (129) (1984) 203–215.
- [29] M. Sanjuan, A. Moragues, Model for predicting plastic shrinkage of polypropylene reinforced mortars, *J. Mater. Sci.* 29 (1994) 2821–2825.
- [30] T. Hoersch, F. Wittmann, Simulation of damage and crack formation in the composite structure of concrete under freeze-thaw cycles, in: *International RILEM Workshop on Frost Resistance of Concrete*, RILEM Publications SARL, 2002.
- [31] O. Buyukozturk, O. Gunes, E. Karaca, Progress on understanding debonding problems in reinforced concrete and steel members strengthened using FRP composites, *Constr. Build. Mater.* 18 (1) (2004) 9–19.
- [32] M. Mazloom, Estimating long-term creep and shrinkage of high-strength concrete, *Cement Concr. Compos.* 30 (4) (2008) 316–326.
- [33] M. Islam, B. Mondal, M. Islam, Effect of sea salts on structural concrete in a tidal environment, *Aust. J. Struct. Eng.* 10 (3) (2010) 237–252.

- [34] A. Mpalaskas, et al., Monitoring of the fracture mechanisms induced by pull-out and compression in concrete, *Eng. Fract. Mech.* 128 (2014) 219–230.
- [35] X. Li, et al., Thermal and mechanical properties of high-performance fiber-reinforced cementitious composites after exposure to high temperatures, *Constr. Build. Mater.* 157 (2017) 829–838.
- [36] C. Xue, et al., Effect of incompatibility between healing agent and cement matrix on self-healing performance of intelligent cementitious composite, *Smart Mater. Struct.* 29 (11) (2020) 115020.
- [37] Y. Wang, et al., Analysis of concrete damage evolution in cold regions under combined freeze-thaw cycle-crack effect, *Constr. Build. Mater.* 456 (2024) 139296.
- [38] F. Aslani, et al., Mechanical and shrinkage performance of 3D-printed rubberised engineered cementitious composites, *Constr. Build. Mater.* 339 (2022) 127665.
- [39] V. Nguyen-Van, et al., Modelling of 3D-printed bio-inspired Bouligand cementitious structures reinforced with steel fibres, *Eng. Struct.* 274 (2023) 115123.
- [40] H. Ogura, V.N. Nerella, V. Mechtcherine, Developing and testing of strain-hardening cement-based composites (SHCC) in the context of 3D-printing, *Materials* 11 (8) (2018) 1375.
- [41] J. Pegna, Exploratory investigation of solid freeform construction, *Autom. Construct.* 5 (5) (1997) 427–437.
- [42] M. Sambucci, M. Valente, Influence of waste tire rubber particles size on the microstructural, mechanical, and acoustic insulation properties of 3D-printable cement mortars, *Civil Engineering Journal* 7 (6) (2021) 937–952.
- [43] T. Ding, et al., Flexural properties of 3D printed fibre-reinforced concrete with recycled sand, *Constr. Build. Mater.* 288 (2021) 123077.
- [44] B. Zhu, et al., Relationship between microstructure and strain-hardening behaviour of 3D printed engineered cementitious composites, *Cement Concr. Compos.* 133 (2022) 104677.
- [45] B. Khoshnevis, Automated construction by contour crafting—related robotics and information technologies, *Autom. Construct.* 13 (1) (2004) 5–19.
- [46] B.R. Utela, et al., Development Process for Custom three-dimensional Printing (3DP) Material Systems, 2010.
- [47] M. Hambach, M. Rutzen, D. Volkmer, Properties of 3D-printed fiber-reinforced Portland cement paste, in: *3D Concrete Printing Technology*, Elsevier, 2019, pp. 73–113.
- [48] Q. Li, et al., Interlayer adhesion strength of 3D-printed cement-based materials exposed to varying curing conditions, *J. Build. Eng.* 74 (2023) 106825.
- [49] T.T. Le, et al., Hardened properties of high-performance printing concrete, *Cement Concr. Res.* 42 (3) (2012) 558–566.
- [50] I. Farina, et al., Surface roughness effects on the reinforcement of cement mortars through 3D printed metallic fibers, *Compos. B Eng.* 99 (2016) 305–311.
- [51] S.A. Nair, A. Tripathi, N. Neithalath, Examining layer height effects on the flexural and fracture response of plain and fiber-reinforced 3D-printed beams, *Cement Concr. Compos.* 124 (2021) 104254.
- [52] U. Kilic, et al., Effects of cellulose nanofibrils on rheological and mechanical properties of 3D printable cement composites, *Cement Concr. Compos.* 152 (2024) 105617.
- [53] V.C. Li, *Engineered Cementitious Composites (ECC) Material, Structural, and Durability Performance*, 2008.
- [54] L.-Y. Xu, et al., Green and Low-Carbon Matrices for Engineered/Strain-Hardening Cementitious Composites (ECC/SHCC): towards sustainable and resilient infrastructure, *J. Clean. Prod.* (2025) 144968.
- [55] Y. Zhou, et al., Development of high strain-hardening lightweight engineered cementitious composites: design and performance, *Cement Concr. Compos.* 104 (2019) 103370.
- [56] M. Maalej, V.C. Li, Flexural/tensile-strength ratio in engineered cementitious composites, *J. Mater. Civ. Eng.* 6 (4) (1994) 513–528.
- [57] K.-T. Yan, et al., Anisotropic size effect of 3D printed LC3-based engineered cementitious composites (LC3-ECC), *J. Build. Eng.* 92 (2024) 109668.
- [58] L.-Y. Xu, et al., Upcycling red mud into high-strength high-ductility Engineered Geopolymer Composites (EGC): toward superior performance and sustainability, *Compos. B Eng.* (2025) 112713.
- [59] B.-T. Huang, et al., Strain-hardening ultra-high-performance Concrete (SH-UHPC) with hybrid steel and polyethylene fibers: enhanced tensile ductility at subzero temperatures, *Theor. Appl. Fract. Mech.* (2025) 104987.
- [60] S.H. Bong, et al., Three-Dimensional-Printed engineered, strain-hardening geopolymer composite as permanent formwork for construction of reinforced concrete beam, *ACI Struct. J.* 121 (2) (2024).
- [61] Z. Wan, et al., Mechanical properties and healing efficiency of 3D-printed ABS vascular based self-healing cementitious composite: experiments and modelling, *Eng. Fract. Mech.* 267 (2022) 108471.
- [62] M. Garg, P. Azarsa, R. Gupta, Self-healing potential and post-cracking tensile behavior of polypropylene fiber-reinforced cementitious composites, *Journal of Composites Science* 5 (5) (2021) 122.
- [63] S. Choi, S.P. Shah, Fracture mechanism in cement-based materials subjected to compression, *J. Eng. Mech.* 124 (1) (1998) 94–102.
- [64] R. Ballarini, S. Shah, L. Keer, Crack growth in cement-based composites, *Eng. Fract. Mech.* 20 (3) (1984) 433–445.
- [65] S. Barbhuiya, B.B. Das, F. Kanavaris, A review of fracture propagation in concrete: fundamentals, experimental techniques, modelling and applications, *Mag. Concr. Res.* 76 (10) (2023) 482–514.
- [66] R. Yang, et al., Experimental study on dynamic mechanics and energy evolution of rubber concrete under cyclic impact loading and dynamic splitting tension, *Constr. Build. Mater.* 262 (2020) 120071.
- [67] G.L. Golewski, The phenomenon of cracking in cement concretes and reinforced concrete structures: the mechanism of cracks formation, causes of their initiation, types and places of occurrence, and methods of detection—a review, *Buildings* 13 (3) (2023) 765.
- [68] E.K. Attiogbe, D. Darwin, Submicrocracking in cement paste and mortar, *Materials Journal* 84 (6) (1987) 491–500.
- [69] H. Chen, D. Liu, Fracture and damage properties of high-strength concrete under cyclic loading, *Constr. Build. Mater.* 360 (2022) 129494.
- [70] T. Guo, et al., Dynamic fracture behavior and fracture toughness analysis of rock-concrete bi-material with interface crack at different impact angles, *Constr. Build. Mater.* 356 (2022) 129286.
- [71] L. Sadowski, et al., Micromechanical properties within the interphase between heterogeneous layers made of cementitious composites, *Constr. Build. Mater.* 215 (2019) 1033–1043.
- [72] M. Tijssens, L. Sluys, E. Van der Giessen, Simulation of fracture of cementitious composites with explicit modeling of microstructural features, *Eng. Fract. Mech.* 68 (11) (2001) 1245–1263.
- [73] J. He, et al., Impact of elevated temperatures on the performance of high-strength engineered cementitious composite, *J. Mater. Civ. Eng.* 33 (9) (2021) 04021222.
- [74] P. Lura, O.M. Jensen, J. Weiss, Cracking in cement paste induced by autogenous shrinkage, *Materials and structures* 42 (2009) 1089–1099.
- [75] T. Huang, et al., Experimental study on crack bridging in engineered cementitious composites under fatigue tensile loading, *Constr. Build. Mater.* 154 (2017) 167–175.
- [76] M. Lan, J. Zhou, M. Xu, Effect of fibre types on the tensile behaviour of engineered cementitious composites, *Frontiers in Materials* 8 (2021) 775188.
- [77] F. Aslani, M. Bastami, Constitutive relationships for normal- and high-strength concrete at elevated temperatures, *ACI Mater. J.* 108 (4) (2011) 355.
- [78] X. You, et al., A review on the modelling of carbonation of hardened and fresh cement-based materials, *Cement Concr. Compos.* 125 (2022) 104315.
- [79] P. Liu, et al., Corrosion monitoring of the reinforced concrete by using the embedded annular piezoelectric transducer, *J. Mater. Res. Technol.* 9 (3) (2020) 3511–3519.
- [80] S. Sneha, et al., Study of the mechanical and corrosion resistance properties of ferrocement, in: *IOP Conference Series: Earth and Environmental Science*, IOP Publishing, 2020.
- [81] Y. Wang, H. Wu, V.C. Li, Concrete reinforcement with recycled fibers, *J. Mater. Civ. Eng.* 12 (4) (2000) 314–319.
- [82] R. Kasemchaisiri, Filling Ability Prediction Model and Use of Industrial Wastes for self-compacting Concrete, Thammasat University, 2007.
- [83] M. Li, V.C. Li, Cracking and healing of engineered cementitious composites under chloride environment, *ACI Mater. J.* 108 (3) (2011) 333.
- [84] M. Szelag, Mechano-physical properties and microstructure of carbon nanotube reinforced cement paste after thermal load, *Nanomaterials* 7 (9) (2017) 267.
- [85] L. Wang, et al., Freeze-thaw resistance of 3D-printed composites with desert sand, *Cement Concr. Compos.* 133 (2022) 104693.

- [86] G. Du, Y. Qian, Effects of printing patterns and loading directions on fracture behavior of 3D printed Strain-Hardening Cementitious Composites, *Eng. Fract. Mech.* 304 (2024) 110155.
- [87] M. Şahmaran, et al., Internal curing of engineered cementitious composites for prevention of early age autogenous shrinkage cracking, *Cement Concr. Res.* 39 (10) (2009) 893–901.
- [88] E. Cuenca, A. Mezzena, L. Ferrara, Synergy between crystalline admixtures and nano-constituents in enhancing autogenous healing capacity of cementitious composites under cracking and healing cycles in aggressive waters, *Constr. Build. Mater.* 266 (2021) 121447.
- [89] J. Cheung, L. Roberts, J. Liu, Admixtures and sustainability, *Cement Concr. Res.* 114 (2018) 79–89.
- [90] C. Gosselein, et al., Large-scale 3D printing of ultra-high performance concrete—a new processing route for architects and builders, *Mater. Des.* 100 (2016) 102–109.
- [91] J. Ye, et al., Flexural behaviors of 3D printed lightweight engineered cementitious composites (ECC) slab with hollow sections, *Eng. Struct.* 299 (2024) 117113.
- [92] T. Diks, *The Roadmap to Standards for 3D Concrete Printing. Research on the Interplay Between Technological and Legislative Developments*, University of Twente, 2019.
- [93] G. Ma, et al., Technology readiness: a global snapshot of 3D concrete printing and the frontiers for development, *Cement Concr. Res.* 156 (2022) 106774.
- [94] T. Pan, et al., How do the contact surface forces affect the interlayer bond strength of 3D printed mortar? *Cement Concr. Compos.* 133 (2022) 104675.
- [95] A. Mostafaei, et al., Binder jet 3D printing—Process parameters, materials, properties, modeling, and challenges, *Prog. Mater. Sci.* 119 (2021) 100707.
- [96] L. Del Giudice, M.F. Vassiliou, Mechanical properties of 3D printed material with binder jet technology and potential applications of additive manufacturing in seismic testing of structures, *Addit. Manuf.* 36 (2020) 101714.
- [97] W. Zhou, et al., Influence of printing parameters on 3D printing engineered cementitious composites (3DP-ECC), *Cement Concr. Compos.* 130 (2022) 104562.
- [98] M. Bekaert, K. Van Tittelboom, G. De Schutter, 3D printed concrete as stay-in-place formwork: mechanics during casting and curing, *Struct. Concr.* 24 (1) (2023) 738–755.
- [99] H. Gao, et al., Rheological behavior of 3D printed concrete: influential factors and printability prediction scheme, *J. Build. Eng.* 91 (2024) 109626.
- [100] H. Lucen, et al., The synergistic effect of greenhouse gas CO₂ and silica fume on the properties of 3D printed mortar, *Compos. B Eng.* 271 (2024) 111188.
- [101] H.G. Şahin, A. Mardani, H.E. Beytekin, Effect of silica fume utilization on structural build-up, mechanical and dimensional stability performance of fiber-reinforced 3D printable concrete, *Polymers* 16 (4) (2024) 556.
- [102] Y. Han, et al., Environmental and economic assessment on 3D printed buildings with recycled concrete, *J. Clean. Prod.* 278 (2021) 123884.
- [103] J. Xiao, et al., Fiber-reinforced mortar with 100% recycled fine aggregates: a cleaner perspective on 3D printing, *J. Clean. Prod.* 319 (2021) 128720.
- [104] A. Vargas, R. Robayo-Salazar, R. Mejía de Gutiérrez, Effects of incorporating fine aggregates and polypropylene microfibres on the cracking control of 3D printed cementitious mixtures, *Buildings* 15 (1) (2024) 55.
- [105] Y. Wang, et al., Hardening properties and microstructure of 3D printed engineered cementitious composites based on limestone calcined clay cement, *Cement Concr. Compos.* 152 (2024) 105641.
- [106] H. Yue, et al., Investigation on applicability of spherical electric arc furnace slag as fine aggregate in superplasticizer-free 3D printed concrete, *Constr. Build. Mater.* 319 (2022) 126104.
- [107] J. Sun, et al., Fibre-reinforced lightweight engineered cementitious composites for 3D concrete printing, *Ceram. Int.* 47 (19) (2021) 27107–27121.
- [108] H. Gou, et al., Combined printable and mechanical analysis of 3D-printed green high-strength, lightweight engineered cementitious composites, *Cement Concr. Compos.* 149 (2024) 105506.
- [109] W. Chen, et al., Printability region for 3D-printable engineered cementitious composites (3DP-ECC), *Cement Concr. Compos.* 151 (2024) 105599.
- [110] Y.W.D. Tay, Y. Qian, M.J. Tan, Printability region for 3D concrete printing using slump and slump flow test, *Compos. B Eng.* 174 (2019) 106968.
- [111] A. Siddika, et al., 3D-printed concrete: applications, performance, and challenges, *Journal of Sustainable Cement-Based Materials* 9 (3) (2020) 127–164.
- [112] T.D. Ngo, et al., Additive manufacturing (3D printing): a review of materials, methods, applications and challenges, *Compos. B Eng.* 143 (2018) 172–196.
- [113] Y. Tang, et al., Trans-layer and inter-layer fracture behavior of extrusion-based 3D printed concrete under three-point bending, *Eng. Fract. Mech.* 296 (2024) 109836.
- [114] N.C. Demiral, et al., Mechanical anisotropy evaluation and bonding properties of 3D-printable construction and demolition waste-based geopolymer mortars, *Cement Concr. Compos.* 134 (2022) 104814.
- [115] B.-Y. Deng, et al., Flexural behavior of precast ultra-lightweight ECC-concrete composite slab with lattice girders, *Eng. Struct.* 279 (2023) 115553.
- [116] S. Liu, et al., A comparative study on environmental performance of 3D printing and conventional casting of concrete products with industrial wastes, *Chemosphere* 298 (2022) 134310.
- [117] A. Danish, et al., Microstructural characterization, driving mechanisms, and improvement strategies for interlayer bond strength of additive-manufactured cementitious composites: a review, *Case Stud. Constr. Mater.* 17 (2022) e01217.
- [118] W. McGee, et al., Extrusion nozzle shaping for improved 3DP of engineered cementitious composites (ECC/SHCC), in: *Second RILEM International Conference on Concrete and Digital Fabrication: Digital Concrete 2020 2*, Springer, 2020.
- [119] Y. Ding, et al., Structural behaviors of ultra-high performance engineered cementitious composites (UHP-ECC) beams subjected to bending-experimental study, *Constr. Build. Mater.* 177 (2018) 102–115.
- [120] M. van den Heever, et al., Evaluating the effects of porosity on the mechanical properties of extrusion-based 3D printed concrete, *Cement Concr. Res.* 153 (2022) 106695.
- [121] N. Aminpour, A. Memari, Analysis of anisotropic behavior in 3D concrete printing for mechanical property evaluation, *J. Build. Eng.* 99 (2025) 111652.
- [122] Z. Li, F. Aslani, Performance of 3D-printed beams and slabs using self-sensing cementitious composites and DIC method, *Sensors* 23 (20) (2023) 8486.
- [123] T.K.N. Quah, et al., Concrete 3D printing: process parameters for process control, monitoring and diagnosis in automation and construction, *Mathematics* 11 (6) (2023) 1499.
- [124] G. Du, Y. Sun, Y. Qian, Nature-inspired approach for enhancing the fracture performance of 3D printed strain-hardening cementitious composites (3DP-SHCC), *Eng. Struct.* 322 (2025) 119074.
- [125] V. Li, *Engineered Cementitious Composites (ECC), Engineered Cementitious Composites (ECC): Bendable Concrete for Sustainable and Resilient Infrastructure*, Springer, Berlin, Germany, 2019.
- [126] G.A. Rao, Long-term drying shrinkage of mortar—Influence of silica fume and size of fine aggregate, *Cement Concr. Res.* 31 (2) (2001) 171–175.
- [127] K. Yu, et al., 3D-printable engineered cementitious composites (3DP-ECC): fresh and hardened properties, *Cement Concr. Res.* 143 (2021) 106388.
- [128] N. Zhang, J. Sanjayan, Extrusion nozzle design and print parameter selections for 3D concrete printing, *Cement Concr. Compos.* 137 (2023) 104939.
- [129] S.A. Khan, et al., The impact of nozzle diameter and printing speed on geopolymer-based 3D-Printed concrete structures: numerical modeling and experimental validation, *Results Eng.* 21 (2024) 101864.
- [130] Y. Asghari, et al., 3D printing and implementation of engineered cementitious Composites-A review, *Case Stud. Constr. Mater.* 21 (2024) e03462.
- [131] V.N. Nerella, S. Hempel, V. Mechtcherine, Effects of layer-interface properties on mechanical performance of concrete elements produced by extrusion-based 3D-printing, *Constr. Build. Mater.* 205 (2019) 586–601.
- [132] K.-T. Yan, et al., 3D-printed LC3-based lightweight engineered cementitious composites: fresh state, harden material properties and beam performance, *J. Build. Eng.* 93 (2024) 109838.
- [133] S. Yang, et al., A predictive model to determine tensile strength and fracture toughness of 3D printed fiber reinforced concrete loaded in different directions, *Theor. Appl. Fract. Mech.* 119 (2022) 103309.
- [134] Y. Xu, B. Savija, Development of strain hardening cementitious composite (SHCC) reinforced with 3D printed polymeric reinforcement: mechanical properties, *Compos. B Eng.* 174 (2019) 107011.
- [135] L. Wang, F. Aslani, Structural performance of reinforced concrete beams with 3D printed cement-based sensor embedded and self-sensing cementitious composites, *Eng. Struct.* 275 (2023) 115266.

- [136] L. Wang, et al., Mechanical behaviors of 3D printed lightweight concrete structure with hollow section, *Arch. Civ. Mech. Eng.* 20 (2020) 1–17.
- [137] M. Qiu, Y. Sun, Y. Qian, Interfacial bonding performance of 3D-printed ultra-high performance strain-hardening cementitious composites (UHP-SHCC) and cast normal concrete, *J. Build. Eng.* 82 (2024) 108268.
- [138] M.K. Mohan, et al., Assessment of pore structure characteristics and tortuosity of 3D printed concrete using mercury intrusion porosimetry and X-ray tomography, *Cement Concr. Compos.* 140 (2023) 105104.
- [139] R. Yang, et al., Anomalous matrix and interlayer pore structure of 3D-printed fiber-reinforced cementitious composites, *Cement Concr. Res.* 157 (2022) 106829.
- [140] Z. Hao, et al., 3D crack recognition in engineered cementitious composites (ECC) based on super-resolution reconstruction and semantic segmentation of X-ray computed microtomography, *Compos. B Eng.* 285 (2024) 111730.
- [141] J. Xiao, et al., Interlayer bonding strength and pore characteristics of 3D printed engineered cementitious composites (ECC), *J. Build. Eng.* 84 (2024) 108559.
- [142] Z. Meng, et al., Unraveling the reinforcing mechanisms for cementitious composites with 3D printed multidirectional auxetic lattices using X-ray computed tomography, *Mater. Des.* 246 (2024) 113331.
- [143] D. Li, et al., Experimental study on fracture and fatigue crack propagation processes in concrete based on DIC technology, *Eng. Fract. Mech.* 235 (2020) 107166.
- [144] G.P. Kaczmarczyk, M. Cala, Possible application of computed tomography for Numerical Simulation of the damage mechanism of cementitious Materials—A method review, *Buildings* 13 (3) (2023) 587.
- [145] A. Ramezani, et al., Effects of different types of fibers on fresh and hardened properties of cement and geopolymer-based 3D printed mixtures: a review, *Buildings* 13 (4) (2023) 945.
- [146] F. Teng, et al., Development of strain-hardening cementitious composites (SHCC) as bonding materials to enhance interlayer and flexural performance of 3D printed concrete, *Cement Concr. Compos.* 152 (2024) 105657.
- [147] W. Zhou, et al., Filament stitching: an architected printing strategy to mitigate anisotropy in 3D-Printed engineered cementitious composites (ECC), *Cement Concr. Compos.* 160 (2025) 106044.
- [148] D. Trinh-Duc, et al., Estimation of post-cracking dissipation capabilities of fiber reinforced concretes in three point bending test monitored with application of digital image correlation system, *Materials* 14 (17) (2021) 5088.
- [149] M. Meurer, M. Classen, Mechanical properties of hardened 3D printed concretes and mortars—Development of a consistent experimental characterization strategy, *Materials* 14 (4) (2021) 752.
- [150] Q. Liu, et al., The printable and hardened properties of nano-calcium carbonate with modified polypropylene fibers for cement-based 3D printing, *Constr. Build. Mater.* 369 (2023) 130594.
- [151] L. Kumar, et al., Experimental and numerical evaluation of multi-directional compressive and flexure behavior of three-dimensional printed concrete, *Front. Struct. Civ. Eng.* 17 (11) (2023) 1643–1661.
- [152] X. Sun, et al., PVA fibre reinforced high-strength cementitious composite for 3D printing: mechanical properties and durability, *Addit. Manuf.* 49 (2022) 102500.
- [153] C. Tang, et al., Preparation and flexural performance of 3D printed gradient negative Poisson's ratio structure reinforced cementitious composites, *J. Build. Eng.* (2025) 111875.
- [154] M. Bai, et al., Experimental and numerical study on the flexural behavior of 3D-printed composite beams with U-shaped ECC formwork, *Eng. Struct.* 312 (2024) 118225.
- [155] Z. Wang, et al., Numerical study on dynamic behavior and microscopic damage mechanism of 3D printed rock-like materials, *Comput. Geotech.* 173 (2024) 106495.
- [156] L.A. Le, et al., Incorporation of micro-cracking and fibre bridging mechanisms in constitutive modelling of fibre reinforced concrete, *J. Mech. Phys. Solid.* 133 (2019) 103732.
- [157] S. Luo, et al., Effects of interval time and interfacial agents on the mechanical characteristics of ultra-high toughness cementitious composites under 3D-printed technology, *Constr. Build. Mater.* 374 (2023) 130936.
- [158] T. Marchment, J. Sanjayan, M. Xia, Method of enhancing interlayer bond strength in construction scale 3D printing with mortar by effective bond area amplification, *Mater. Des.* 169 (2019) 107684.
- [159] K.M. Nemati, Fracture analysis of concrete using scanning electron microscopy, *Scanning* 19 (6) (1997) 426–430.
- [160] K. Zhang, et al., Quantitative characterization of defects in stereolithographic additive manufactured ceramic using X-ray computed tomography, *J. Mater. Sci. Technol.* 118 (2022) 144–157.
- [161] K. Zhang, et al., A review of defects in vat photopolymerization additive-manufactured ceramics: characterization, control, and challenges, *J. Eur. Ceram. Soc.* 44 (3) (2024) 1361–1384.
- [162] V. Nguyen-Van, et al., Extended finite element multiscale modelling for crack propagation in 3D-printed fibre-reinforced concrete, *Addit. Manuf.* 81 (2024) 104019.
- [163] B. Yin, L. Zhang, Phase field method for simulating the brittle fracture of fiber reinforced composites, *Eng. Fract. Mech.* 211 (2019) 321–340.
- [164] S. Zhou, et al., Modeling microcapsule-enabled self-healing cementitious composite materials using discrete element method, *Int. J. Damage Mech.* 26 (2) (2017) 340–357.
- [165] A. Yaghoobi, et al., Mesoscale fracture analysis of multiphase cementitious composites using peridynamics, *Materials* 10 (2) (2017) 162.
- [166] A. Spagnoli, A micromechanical lattice model to describe the fracture behaviour of engineered cementitious composites, *Comput. Mater. Sci.* 46 (1) (2009) 7–14.
- [167] A. Farsi, et al., Simulation of fracture propagation in fibre-reinforced concrete using FDEM: an application to tunnel linings, *Computational Particle Mechanics* 7 (2020) 961–974.
- [168] Z. Omar, et al., Predicting the flexural behaviour of CFRP-strengthened concrete beam using combined XFEM and cohesive zone model, *Journal of Applied Science and Engineering* 25 (6) (2022) 1077–1090.
- [169] L. Dong, et al., Interface bonding characteristics of 3D printed ultra-high performance concrete after elevated temperatures, *J. Build. Eng.* 93 (2024) 109801.
- [170] G. Ma, et al., A novel additive mortar leveraging internal curing for enhancing interlayer bonding of cementitious composite for 3D printing, *Constr. Build. Mater.* 244 (2020) 118305.
- [171] A. Raza, et al., Comprehensive study on the microstructural and mechanical performance of 3D-printed engineered cementitious composites with yellow river sand integration, *J. Build. Eng.* 108 (2025) 112973.
- [172] A. Abrishambaf, M. Pimentel, S. Nunes, Influence of fibre orientation on the tensile behaviour of ultra-high performance fibre reinforced cementitious composites, *Cement Concr. Res.* 97 (2017) 28–40.
- [173] Q. Shen, et al., Fresh and anisotropic-mechanical properties of polyoxymethylene fibers reinforced 3D printable cementitious composites, *J. Build. Eng.* (2025) 112140.
- [174] Z. Pang, et al., A multiscale model for quantifying fiber orientation effects on the tensile properties of 3D printed Engineered Cementitious Composites (3DP-ECC), *J. Build. Eng.* 68 (2023) 106090.
- [175] D.-Y. Yoo, N. Banthia, Mechanical properties of ultra-high-performance fiber-reinforced concrete: a review, *Cement Concr. Compos.* 73 (2016) 267–280.
- [176] C. Camille, et al., Post-cracking strength classification of macro-synthetic fibre reinforced concrete for sleeper application, in: *Fibre Reinforced Concrete: Improvements and Innovations: Rilem-Fib International Symposium on FRC (BEFIB) in 2020 10*, Springer, 2021.
- [177] S. Rawat, C. Lee, Y. Zhang, Performance of fibre-reinforced cementitious composites at elevated temperatures: a review, *Constr. Build. Mater.* 292 (2021) 123382.
- [178] N.P. Tran, et al., Microstructural characterisation of cementitious composite incorporating polymeric fibre: a comprehensive review, *Constr. Build. Mater.* 335 (2022) 127497.

- [179] A. Peled, H. Guttman, A. Bentur, Treatments of polypropylene fibres to optimize their reinforcing efficiency in cement composites, *Cement Concr. Compos.* 14 (4) (1992) 277–285.
- [180] S. He, et al., Strain hardening ultra-high performance concrete (SHUHPC) incorporating CNF-coated polyethylene fibers, *Cement Concr. Res.* 98 (2017) 50–60.
- [181] M.M. Jaberizadeh, et al., Eco-efficient cementitious composites using waste cellulose fibers: effects on autogenous shrinkage, strength and energy absorption capacity, *Constr. Build. Mater.* 408 (2023) 133504.
- [182] J. Morton, The work of fracture of random fibre reinforced cement, *Matériaux et Construction* 12 (1979) 393–396.
- [183] H. Nguyen, et al., Strain hardening polypropylene fiber reinforced composite from hydrated ladle slag and gypsum, *Compos. B Eng.* 158 (2019) 328–338.
- [184] B. Shafei, et al., State-of-the-art review of capabilities and limitations of polymer and glass fibers used for fiber-reinforced concrete, *Materials* 14 (2) (2021) 409.
- [185] J. Zhou, et al., Effect of directionally distributed steel fiber on static and dynamic properties of 3D printed cementitious composite, *Constr. Build. Mater.* 318 (2022) 125948.
- [186] M. Rutzen, et al., 3D printing as an automated manufacturing method for a carbon fiber-reinforced cementitious composite with outstanding flexural strength (105 N/mm²), *Mater. Struct.* 54 (2021) 1–20.
- [187] L. Shi, Y. Lu, Y. Bai, Mechanical and electrical characterisation of steel fiber and carbon black engineered cementitious composites, *Procedia Eng.* 188 (2017) 325–332.
- [188] L. Wang, et al., Shrinkage and cracking performance of PP/PVA fiber-reinforced 3D-printed mortar, *J. Mater. Civ. Eng.* 35 (6) (2023) 04023132.
- [189] N. Shabakhty, H.R. Karimi, A.Y. Bakhtiary, Effect of short to long hybrid elastic/hyperelastic (Glass/PP) fibers on high-strength engineered cementitious composites (ECC), along with presenting a constitutive model, *J. Build. Eng.* 89 (2024) 109215.
- [190] B. Liu, et al., Study on the fracture behavior and anisotropy of 3D-printing PVA fiber-reinforced concrete, *Constr. Build. Mater.* 447 (2024) 138051.
- [191] Y. Zhang, F. Aslani, Development of fibre reinforced engineered cementitious composite using polyvinyl alcohol fibre and activated carbon powder for 3D concrete printing, *Constr. Build. Mater.* 303 (2021) 124453.
- [192] A. Nasr, et al., Enhancing mechanical properties of 3D printed cementitious composites utilizing hybrid recycled PP and PET fibers, *Constr. Build. Mater.* 455 (2024) 139179.
- [193] J. Pan, et al., Impact behaviour of 3D printed fiber reinforced cementitious composite beams, *Compos. Appl. Sci. Manuf.* 182 (2024) 108175.
- [194] J. Van Der Putten, et al., Development of 3D printable cementitious composites with the incorporation of polypropylene fibers, *Materials* 14 (16) (2021) 4474.
- [195] F.P. Bos, E. Bosco, T.A. Salet, Ductility of 3D printed concrete reinforced with short straight steel fibers, *Virtual Phys. Prototyp.* 14 (2) (2019) 160–174.
- [196] E. Igbokwe, et al., Self-healing of macroscopic cracks in concrete by cellulose fiber carried microbes, *J. Build. Eng.* 90 (2024) 109383.
- [197] H. Zhang, et al., Effect of fiber content and alignment on the mechanical properties of 3D printing cementitious composites, *Materials* 14 (9) (2021) 2223.
- [198] A.R. Arunothayan, et al., Fiber orientation effects on ultra-high performance concrete formed by 3D printing, *Cement Concr. Res.* 143 (2021) 106384.
- [199] M. Singh, B. Saini, H. Chalak, Performance and composition analysis of engineered cementitious composite (ECC)—A review, *J. Build. Eng.* 26 (2019) 100851.
- [200] Y. Ding, et al., 3D printing hybrid-fiber reinforced engineered cementitious composites (3DP-HECC): feasibility in long-open-time applications, *Constr. Build. Mater.* 445 (2024) 137960.
- [201] R. Srinivasan, D. DeFord, S.P. Shah, The use of extrusion rheometry in the development of extruded fiber-reinforced cement composites, *Concrete Science and Engineering* 1 (1) (1999) 26–36.
- [202] D.-Y. Yoo, et al., Effects of fiber shape, aspect ratio, and volume fraction on flexural behavior of ultra-high-performance fiber-reinforced cement composites, *Compos. Struct.* 174 (2017) 375–388.
- [203] B. Ali, L.A. Qureshi, Influence of glass fibers on mechanical and durability performance of concrete with recycled aggregates, *Constr. Build. Mater.* 228 (2019) 116783.
- [204] M. Li, et al., Modeling and experimental investigation of fiber orientation in cast and 3D-printed cementitious composites, *Mater Sci Addit Manuf* 2 (3) (2023) 1603.
- [205] A.W.F. Coelho, R.M.d.S.M. Thiré, A.C. Araujo, Manufacturing of gypsum–sisal fiber composites using binder jetting, *Addit. Manuf.* 29 (2019) 100789.
- [206] K. Nefs, et al., Orientation Dependency of 3D printed SHCC at increasing length scale, *Cement Concr. Compos.* 149 (2024) 105515.
- [207] D.G. Soltan, V.C. Li, A self-reinforced cementitious composite for building-scale 3D printing, *Cement Concr. Compos.* 90 (2018) 1–13.
- [208] X. Yao, et al., Review of mechanical and temperature properties of fiber reinforced recycled aggregate concrete, *Buildings* 12 (8) (2022) 1224.
- [209] J. Liu, et al., 3D printing of cementitious mortar with milled recycled carbon fibres: influences of filament offset on mechanical properties, *Cement Concr. Compos.* 142 (2023) 105169.
- [210] M. Garg, C.S. Das, Use of silica particles to improve dispersion of-COOH CNTs/carbon fibers to produce HyFRCC, *Constr. Build. Mater.* 250 (2020) 118777.
- [211] F.J. Baeza, et al., Effect of aspect ratio on strain sensing capacity of carbon fiber reinforced cement composites, *Mater. Des.* 51 (2013) 1085–1094.